BEHAVE Wildland Fine Fuel Moisture Model:

Field Testing and Sensitivity Analysis

Coop Agreement of U. of Montana

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COMPLETION REPORT

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ABSTRACT

The computer modeling system, BEHAVE, was developed by the USFS Intermountain Fire Sciences Laboratory to assist in predicting wildland fire behavior. Critical to such predictions is knowledge of the moisture content of fine fuels. The objectives of this study were to test the accuracy of the fine fuel moisture model used within the BEHAVE system, to compare its accuracy with that of the Fire Behavior Officer (FBO) and Fine Fuel Moisture Code (FFMC) models, and to characterize the sensitivity of the BEHAVE model. Field fine fuel moisture values, collected from fuel beds of orchardgrass (*Dactylus glomerata*) stems and leaves and ponderosa pine (*Pinus ponderosa*) needles, were compared with those predicted by BEHAVE, the FFMC, and the FBO models. Open and closed canopy conditions on north and south aspects were tested. Comparisons were made by examining the frequency distributions of the relative allowable error (RAE) of the model predictions. Graphic methods were used for sensitivity analysis.

RAE analysis indicated that BEHAVE was the best predictor of early-afternoon fine fuel moisture; the FBO model was next-best, then the FFMC. The driest site conditions were best represented by the FBO model; moderately moist needle fuels by BEHAVE; and moderately moist grass fuels by the FFMC. No model predicted well for very moist site conditions, although BEHAVE was the most accurate. All models were less accurate late in the season and when rain had fallen within three days; BEHAVE and the FBO model surpassed the FFMC, however. No model predicted well on a diurnal basis. Sensitivity analysis showed that interactions between variables within the BEHAVE model have a larger effect on fine fuel moisture than do single factors. No variables were found with low model sensitivity; further study is recommended if model refinement is desired.

Keywords: wildland fire, fire behavior, fine fuel moisture, BEHAVE, fire modeling.

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INTRODUCTION

Researchers and fire managers need to be able to accurately predict wildland fire behavior in order to train personnel and to make decisions regarding fire suppression, prescribed burning, and contingency planning, and to train personnel via simulated fire situations. To this end, researchers at the U. S. Forest Service Intermountain Fire Sciences Laboratory (IFSL) have developed the comprehensive computer modeling system, BEHAVE.

The BEHAVE system is an integrated package of computer models which estimate individual components of fire behavior (Burgan and Rothermel 1984, Andrews 1986). Knowledge of the moisture content of fine fuels, defined as dead foliage and fine twigs less than one-quarter inch in diameter (Fosberg and Deeming 1971), is critical to predictions of fire behavior components. The moisture content of fine fuels governs the probability of ignition, rate of forward spread, intensity, flame length, and size of wildland fires (Barrows 1951, Rothermel 1983).

The method of predicting fine fuel moisture within the BEHAVE system was developed by Rothermel et al. (1986), but has not been independently validated. Therefore, the present study was conceived, to investigate the accuracy of prediction of the BEHAVE fine fuel moisture model over a

wide range of conditions. This information will prove useful to further refine the model, and to obtain more accurate predictions of fire behavior.

OBJECTIVES

The objectives of this study are three-fold:

1. To test the accuracy of BEHAVE predictions against field observations of fine fuel moisture.
2. To compare predictions of the BEHAVE model with those given by two of its predecessors, the Canadian Fine Fuel Moisture Code (FFMC) and the Fire Behavior Officer (FBO) procedure.
3. To characterize, by graphic means, the sensitivity of the BEHAVE moisture model to its hierarchy of inputs, in order to identify which variables have the largest effect on fine fuel moisture, and which may be discarded because of low model sensitivity.

METHODS

FIELD DESIGN

Four study sites were chosen in the Woods Gulch drainage near Missoula, Montana (T14N, R18W, SW31; lat. 46 deg. 55' N., long. 113 deg. 55' W.); two on a north aspect and two on a south aspect. On each aspect, natural areas of both open and closed canopies were located. Some physical characteristics of these sites are listed in Table 1. The habitat type (Pfister et al. 1977) was Douglas-fir/ninebark (PSME/PHMA) on the south aspect, and Douglas-fir/blue huckleberry (PSME/VAGL) on the north aspect.

On each site, ten man-made fuel beds were placed at random within a 100-square-meter grid. Litter, shrubs, and herbaceous material already present at each random location were cleared away by hand, to provide direct contact between fuel beds and the soil surface. Man-made fuel beds were used to avoid live shrub and herb ingrowth which would detract from the accuracy of fine fuel moisture measurements. Fuel beds consisted of one meter square wood frames with nylon netting stretched across the bottom to help ensure that air and moisture were free to move to all parts of the bed (see Figure 1). A wooden slat divided each frame into halves. Random selection determined whether halves were oriented horizontally or vertically,

and which fuel was assigned to each half.

TABLE 1: PHYSICAL CHARACTERISTICS OF STUDY SITES

SITE CONDITION*	ELEV. (FT.)	ASPECT (DEG.)	SLOPE (%)	%CROWN CLOSURE	OVERSTORY SPP.	TREE HT. (FT.)
SOG/SON	5360	180	16	0	none	0
SCG/SCN	5360	180	21	60	DF+	60
NOG/NON	5360	0	9	0	none	0
NCG/NCN	5360	0	14	90	DF-WL++	30

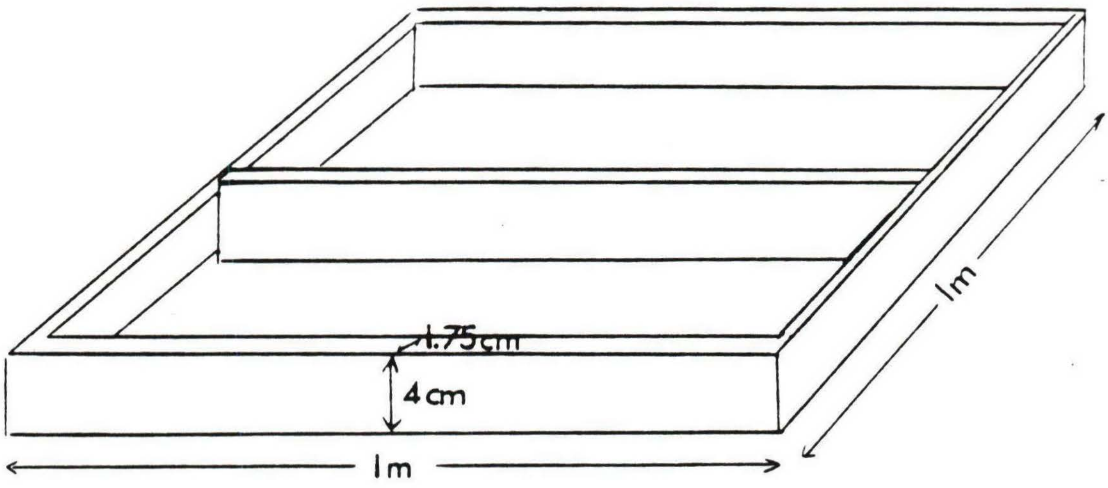
*Named by aspect, canopy closure, and fuel type.
(Ex: SOG=South aspect, Open canopy, Grass fuels.)
+Douglas-fir (*Pseudotsuga menziesii*)
++Western larch (*Larix occidentalis*)

Dry ponderosa pine (*Pinus ponderosa*) needles, a mixture of varied ages (all at least two years old) obtained from stockpiles at the ISFL, were placed on one half. These had been kept under shelter at the ISFL, so were intact, and little weathered. Stems and leaves of orchardgrass (*Dactylus glomerata*), hand-cut and oven-dried, were placed whole on the other half of each bed, so that they were lying down, rather than standing upright. Fuels were placed so that their depth in each bed was approximately 6 cm.

Five "replacement fuel beds" were also placed on each site, to hold fresh fuels that were used to replenish each sampling bed at the close of a sampling session, in order to maintain a constant depth of fuels in the beds and to

allow sufficient time for the fuels to equilibrate with their surroundings before sampling was begun.

FIG. 1: DIAGRAM OF FUEL BED CONSTRUCTION



Standard weather shelters were placed in the open-canopied area on each aspect, four and one-half feet off the ground. Each station was equipped with a hair hygrothermograph, standard rain gauge, and cup anemometer. The instruments measured temperature and relative humidity, precipitation, and twenty-foot windspeed, respectively, for use as inputs to the fine fuel moisture models. Temperature, relative humidity, and windspeed were recorded

hourly; precipitation was measured daily at 2:00 p.m. Anemometer movements were charted using a Young recorder on the south aspect, and a Campbell datalogger on the north aspect.

SAMPLING PROCEDURES

Two sampling schemes were devised to permit the prediction of both early-afternoon and round-the-clock values of fine fuel moisture via BEHAVE.

To test the early-afternoon ("daily") predictive capabilities, field samples were taken each day, as close as possible to 2:00 p.m., for a period of ten days, beginning after a rainfall. Three ten-day sampling sessions were conducted, one in late July/early August, one in late August, and one in late September/early October of 1984. On each day, one sample of needles and one of grass fuels were taken from each of the ten beds on each of the four sites. Each sample, approximately 25-30 grams of material, was placed in a soil tin, sealed tightly with electrical tape to prevent moisture loss, and stored in a burlap bag to protect it from sunlight. Samples were taken directly from the field to the laboratory to be weighed and oven-dried for twenty-four hours for determination of fine fuel moisture content on a dry-weight basis. The ten

samples of each fuel type on each site were then averaged to provide one estimate of fine fuel moisture per fuel type per site. Although averaging obscured the variation in fuel moisture, it was necessary to avoid sampling microsite differences.

In order to test BEHAVE's diurnal predictions, two twenty-four hour sampling sessions were employed during August of 1984. Samples were taken every two hours, beginning at noon on one day and continuing through noon of the next day. For times close to sunrise and sunset, when fuel moisture changes rapidly (Rothermel et al. 1986), sampling was done hourly. Time did not permit the sampling of all ten beds on each site; therefore, five were chosen at random. One sample was taken of each fuel type from five of the ten beds on each site and placed in a paper "lunch bag." Sample wet weights were determined in the field, using a digital Sartorius scale powered by a gasoline generator equipped with a voltage regulator. Samples were taken to the laboratory for determination of fine fuel moisture content on a dry-weight basis. The moisture contents of the five samples of each fuel type from each site were averaged for each hour sampled, to provide one estimate per fuel type per site per hour.

MODEL PREDICTIONS AND EXECUTION

The primary purpose of the BEHAVE Fine Fuel Moisture Model is to predict a "daily value;" that is, to predict moisture in the early afternoon, between 2:00 and 4:00, on any given day. It does this by requesting the fuel moisture (measured or estimated) on the day preceding a rainfall, if one has occurred within the previous week. BEHAVE then generates the fuel moisture on each successive day, using any weather observations available, until the day for which a prediction is desired is reached. A variety of options exist for initiating a moisture calculation, depending on the information available to the user.

The BEHAVE model is also designed to predict diurnal values of fine fuel moisture for any time between 2:00 p.m. of one day through noon of the next day, using the 2:00 and prediction-time weather parameters and the previous day's 2:00 p.m. fuel moisture data. If prediction for times between sunset and the next day's sunrise is desired, the model also requires sunset weather data, and if prediction is to be done for times after the next day's sunrise, the sunrise weather data must be provided as well. BEHAVE estimates weather data for all hours other than 2:00 p.m., sunset, sunrise, and prediction time, which reduces the input from that required by the FFMC, for which the user

must supply weather data for every hour between and including 2:00 p.m. and prediction time.

The weather and environmental data appropriate for each daily and diurnal sampling time were input to the BEHAVE fine fuel moisture model, to obtain predictions of the actual fuel moisture sampled in the field. These data were also input to the FFMC and the FBO models, for daily predictions, so that their output could be compared with that of BEHAVE. Since the FBO model was not designed for diurnal prediction, diurnal comparisons were confined to those between BEHAVE and the FFMC. BEHAVE estimates of hourly temperature and relative humidity were also compared to actual weather data for the two diurnal periods, in order to evaluate the effect of BEHAVE's estimates on the accuracy of diurnal predictions. Daily cases in which the observed fuel moisture exceeded 30%, the approximate threshold value for the ignition of dead fuels (Wright and Bailey 1982), were discarded. There were no diurnal cases for which the observed fuel moisture exceeded 30 %.

Table 2 lists the inputs to the BEHAVE model. Latitude and elevation were read from topographic quadrangle maps. Aspect, slope, crown closure, crown length and diameter, tree height, and fuel depth were determined in the field. Aspect was measured from the center of each plot. Slope was measured as the slope from the bottom to the top of each plot. Crown closure was an

ocular estimate for each stand. Crown length and diameter were averaged for each stand. All trees present on the plot on the south aspect were measured. On the north aspect, the large number of trees made this impractical. Here, the plot was divided into four quadrants for sampling tree measurements; five trees from each quadrant were sampled, and these data averaged.

TABLE 2: LIST OF BEHAVE MODEL INPUTS

1. Instrument Elevation, 0-15,000 ft.
2. Fuel Elevation, 0-15,000 ft.
3. Latitude, -90 to 90 degrees
4. Aspect, 0-360 degrees
5. Percent Slope, 0-300%
6. Crown Closure, 0-100%
7. Crown Length, 0-300.0 ft.
8. Crown Length/Diameter Ratio, 0-10.0 (dimensionless)
9. Tree Type Code (1=conifer, 2=deciduous)
10. Tolerance Code (0=no leaves, 1=intolerant, 2=med. tolerant, 3=very tolerant)
11. Tree Height, 0-300.0 ft.
12. Fuel Depth, 0-10.0 ft.
13. Wind Adjustment Factor, 0-1 (dimensionless)
14. Month, 1-12
15. Day, 1-31
16. Period Length, 1.0-7.0 days
17. Initial Fuel Moisture, 0-100%
18. Projection Time, 24-hr. basis (14.0-36.0 hrs.)
19. Airmass Constancy Code (1=changing, 2=unchanging)
20. 1400-Hour Transparency Code, 0.6-0.8 (dimensionless)
21. Next Sunrise Transparency Code, 0.6-0.8 (dimensionless)
22. Time of Sunrise, 24-hr. basis (14.0-36.0)
23. Time of Sunset, 24-hr. basis (14.0-36.0)
24. Temperature at 1400 Hours, F.
25. Relative Humidity at 1400 Hours, %
26. 20-ft. Windspeed at 1400 Hours, mph
27. Rainfall at 1400 Hours, in. — ea. day in period
28. Cloud Cover at 1400 Hours, %
29. Transition-time Temperature, F.
30. Transition-time Relative Humid., % — up to 3 times
31. Transition-time Windspeed, mph — (sunset, sunrise,
32. Transition-time Cloud Cover, % — & projection time)

For all model runs in this study, stand tolerance was given a value of 2 (moderate shade tolerance).

The wind adjustment factor, a correction applied by BEHAVE to the twenty-foot windspeed for crown closures above ten percent, provides an estimate of the windspeed at fuel level which is reduced by surface roughness (Albini and Baughmann 1979, Rothermel 1983). In this study, no wind adjustment factor was used by the model for the two open-canopied sites. The closed stand on the south aspect was given a value of 0.3; the closed stand on the north aspect, a value of 0.1.

Period length refers to the number of days that the "prediction day" (the day for which a fine fuel moisture prediction is desired) is removed from the day on which the initial fuel moisture is taken.

The initial fuel moisture, for early-afternoon predictions, is the last fuel moisture taken at 2:00 p.m. prior to a rainfall event. For diurnal moisture predictions, the initial fuel moisture is the 2:00 p.m. value from the previous day.

Projection time refers to the time of day for which a fuel moisture prediction is desired. Model runs in this study contained values for projection time which were consistent with the time the fuels were sampled in the field.

Airmass constancy is used by BEHAVE to estimate

missing weather data. No weather data were missing in the course of this study; thus, airmass constancy was never used as a model input.

Atmospheric transparency is a table value which accounts for the effects that atmospheric moisture and haze have on direct solar irradiation. This value ranges from 0.6, for dense haze, to 0.8 for a very clear atmosphere, with 0.745 defined as a "clean forest atmosphere" (Kondratyev 1969). For the purposes of this study, atmospheric transmissivity, both at sunrise and at 2:00 p.m.,was always taken as 0.7. This seemed reasonable, considering the proximity of the study sites to the light summertime smog of the Missoula Valley.

The weather variables, temperature, humidity, and windspeed, were measured at the onsite weather stations. Cloud cover observations were taken from National Weather Service data collected at Bonner, MT, a distance of approximately three air miles from the study sites.

DATA ANALYSIS

Individual t-tests were run on each pair of BEHAVE predictions and field observations of fine fuel moisture, to check the accuracy of the model. The null hypothesis tested was that the BEHAVE prediction was the true

population mean for fine fuel moisture content. Similar t-tests were also run on pairs of FBO predictions and field observations, and on pairs of FFMC predictions and field observations, to check the accuracy of these models. The null hypotheses tested were that the FBO prediction was the true population mean, and that the FFMC prediction was the true population mean. All t-tests were performed at the 5% significance level.

It was recognized that statistical significance does not necessarily imply practical significance in terms of accuracy of fine fuel moisture predictions; therefore, model predictions were also analyzed by the relative allowable error (RAE) method. Relative allowable error values were computed as follows:

$$RAE = \left| \frac{(\text{Observed FFM} - \text{Predicted FFM})}{\text{Observed FFM}} \right| \times 100$$

Dividing the numerator of this equation by the first term in the numerator put the error calculations on a relative, rather than absolute, basis. Analysis in absolute terms was not appropriate for this study, since any determination of the accuracy of prediction needed by fire managers must be based on the fine fuel moisture itself. For example, a difference of 3% moisture between observed and predicted values may not be of practical significance when the fuel

moisture is 15%, but at 5% moisture, it would be more critical. Analysis in relative terms provided a standardized method by which to judge model performance.

RAE values were divided into twenty equally-spaced classes, and the frequency of model predictions in each RAE class determined. Model accuracy was determined by examination of these frequency distributions, using the following criteria:

1. Percentage of the distribution within the first two frequency classes (within 20% RAE).
   Ideally, a model which predicts well should have a left-skewed distribution, with most of the predictions close to the observed values.
2. Percentage of the distribution within the first frequency class (within 10% RAE). The ideal situation is to have a greater percentage in the first class than in the second class.
3. Length of the right tail of the distribution. A short right tail indicates a compact distribution, with few predictions that are very far from the observed values.

SENSITIVITY ANALYSIS

Due to the large number of inputs to the BEHAVE fine fuel moisture model, a traditional sensitivity analysis, in which one variable at a time is changed incrementally while others are held constant, was not possible. As an alternative, Ralph Wilson, researcher at the USFS IFSL, isolated the physical equations within the model which determine the main components of fine fuel moisture, in a hierarchical approach with four levels (diagrammed in Figure 2). In the first level, fine fuel moisture was seen as the direct result of five factors: fuel relative humidity, fuel temperature rise, initial fuel moisture, windspeed, and rainfall. In the second level, fuel temperature rise was broken down into three factors: fuel height, solar intensity, and windspeed. In the third level, solar intensity was seen as the result of four factors: haze, shade, solar elevation angle, and elevation. Finally, in the fourth level, shade was broken down into ten factors: crown length/diameter ratio, crown closure, tree height, aspect, latitude, month, solar elevation, tolerance, percent slope, and cloud cover. 69 selected combinations of three or four factors at a time (for example, "shade by solar intensity and haze at 10,000 ft. elevation") were then graphed by Mr. Wilson. Combinations used were determined in advance by a panel consisting of

the authors and three researchers at the IFSL: Richard Rothermel, Ralph Wilson, and Glen Morris. These graphs do not represent all possible combinations of all factors, but were chosen to show as many factors as was deemed practical and useful. 32 graphs were chosen to show the fourth-level factors, 16 graphs to show the third-level factors, 8 graphs to show the second-level factors, and 13 graphs to show the first-level factors. Inspection of these graphs then revealed the relationships between variables at each level of hierarchy.

Baseline values, listed in Table 3, were used for sensitivity analyses. All variables not examined in a particular graph took on these baseline values. Their use kept sources of variation at a minimum and provided a degree of continuity throughout the analysis, as the model was broken into four levels.

The sensitivity analysis portion of this study remained completely separate from the field testing portion. Arbitrary values of model inputs used for sensitivity analysis had no connection with values used during field testing.

FIGURE 2: HIERARCHICAL RELATIONSHIP OF BEHAVE INPUTS FOR SENSITIVITY ANALYSIS

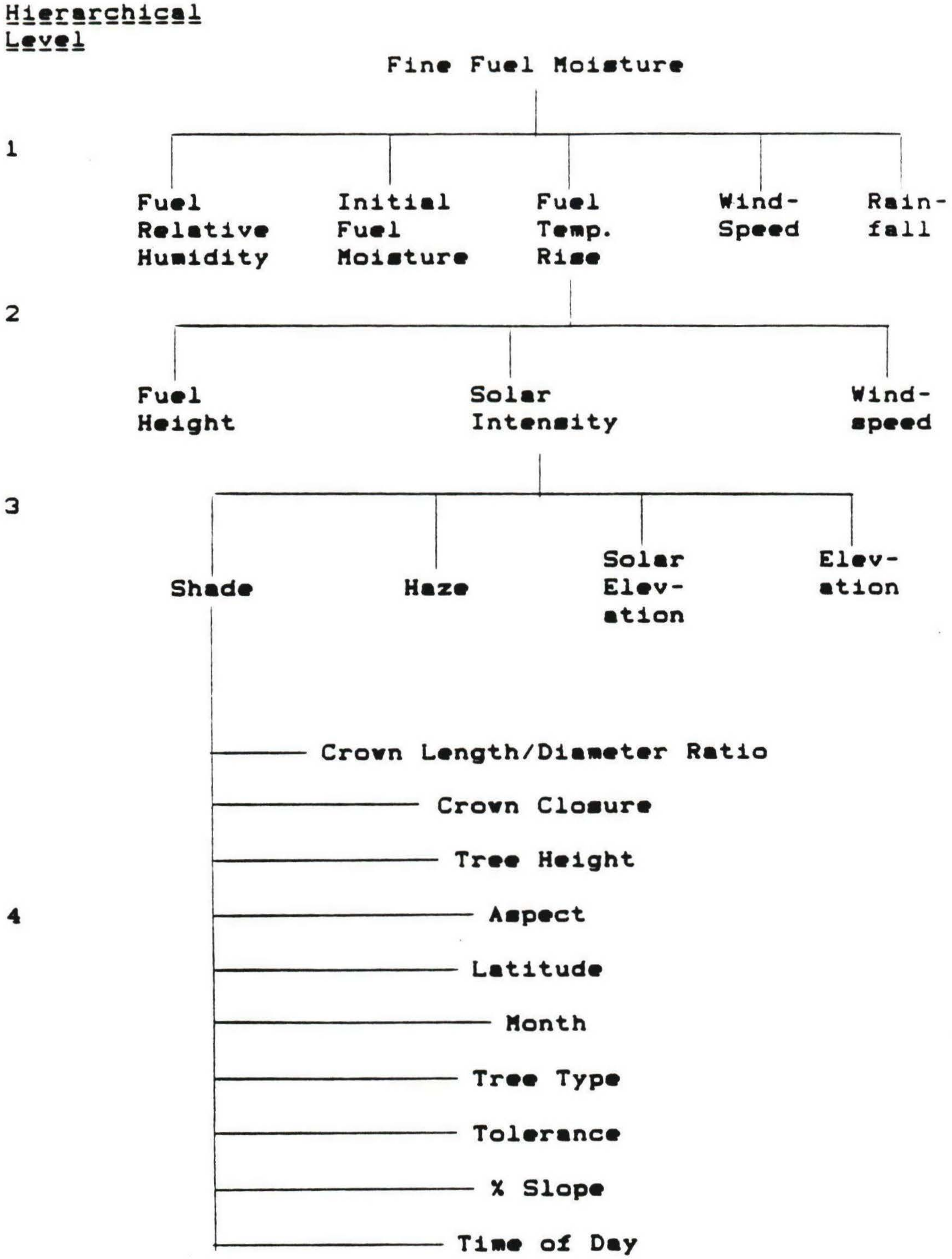


TABLE 3: BASELINE VALUES OF INPUTS FOR SENSITIVITY ANALYSIS

MODEL INPUT	BASELINE VALUE
Fuel & instrument elevation	0 ft.
Latitude	45 degrees N.
Aspect	180 degrees
Slope	0%
Crown closure	50%
Crown height	30 ft.
Crown height/diameter	2.5
Tree type	1
Tree tolerance	2
Tree height	50 ft.
Fuel depth	0.5 ft.
Month	June
Day	21
Period length	3
Initial fuel moisture	10%
Projection time	12:00 pm
1400-hr. transparency	0.745
Next sunrise transparency	0.745
Temperature, 1400 hrs.	75 degrees F.
Relative humidity, 1400 hrs	30%
Windspeed, 1400 hrs	5 mph
Rainfall, 1400 hrs	0 in.
Cloud cover, 1400 hrs	0%

RESULTS

COMPARISONS OF ACTUAL VS. PREDICTED FINE FUEL MOISTURE

Daily Values

Field measurements and model estimates of early-afternoon fine fuel moisture for each site condition over time are shown in Figures 3 through 10. Two-tailed t-tests indicated that each of the three models was usually able to predict well for at least one out of the eight site conditions on each day, although none of the models was able to consistently predict well for all treatments on all days, nor to predict well on the same treatments every day (see Table 4). Of a total of 127 predictions made by each model, BEHAVE's were statistically accurate 26% of the time, the FFMC's, 29% of the time, and the FBO's, 25% of the time.

However, statistics may not be the best way to evaluate these data in terms of their use in predicting fire behavior. A difference of half a percent fuel moisture between observed and predicted values may be rejected statistically, if the variance about the observed values is low, yet a range of half a percent is doubtless sufficiently accurate for fire management purposes. Analysis on the basis of relative allowable error (RAE) may

be more appropriate than on the basis of statistically significant differences. However, standards have not been established for accuracy of fine fuel moisture necessary for fire managers; this is largely dependent on site, weather, season, and management objectives. Individuals, then, must determine the level of RAE that is acceptable to them.

Results of analysis of model predictions by the RAE method are shown in Figures 11 through 13. The BEHAVE model was the best predictor, followed closely by the FBO model, then the FFMC. 51% of BEHAVE's fine fuel moisture estimates fell within 20% RAE, compared to 45% for the FBO model, and 38% for the FFMC. Results of RAE analysis by site condition are presented in Table 5. BEHAVE was the best predictive model for four of the site conditions; the FBO and FFMC models each excelled on two site conditions.

Results of RAE analysis by period length are presented in Table 6. When period length was short (one to two days following a rainfall), BEHAVE was the best predictor of fine fuel moisture. The FFMC improved considerably when period length was three days, although it was surpassed by BEHAVE and the FBO model. Only when period length was four to seven days did the FFMC achieve the accuracy of BEHAVE, but neither of these were as accurate as the FBO model.

Results of RAE analysis by time of year are shown in Table 7. When site conditions were pooled, the FBO model

was the most accurate model for all three time periods, although for the late September/early October period, model accuracy was so low that this distinction is meaningless.

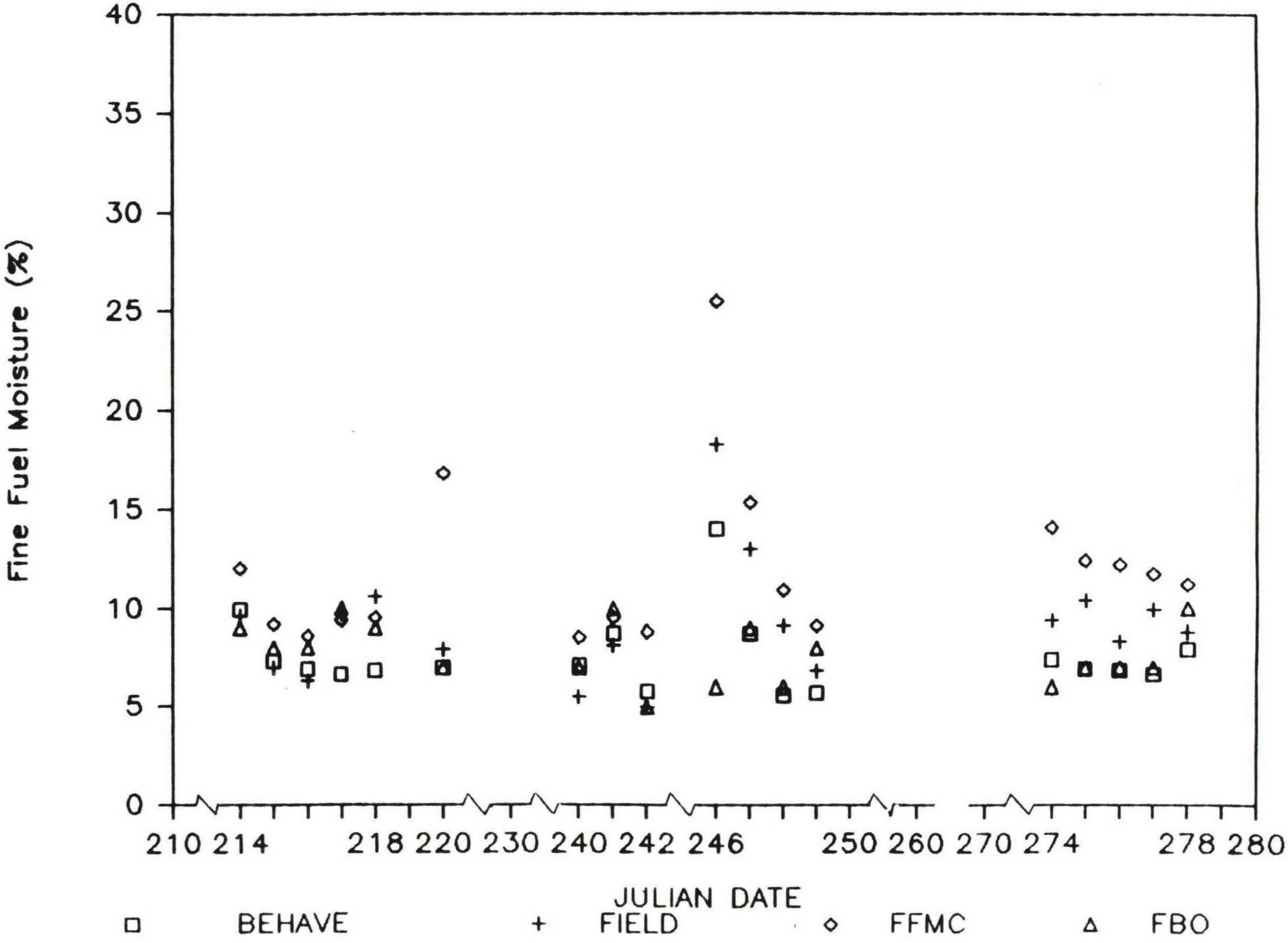


FIGURE 3: DAILY FFM (S. ASPECT, OPEN CANOPY, GRASS FUELS)

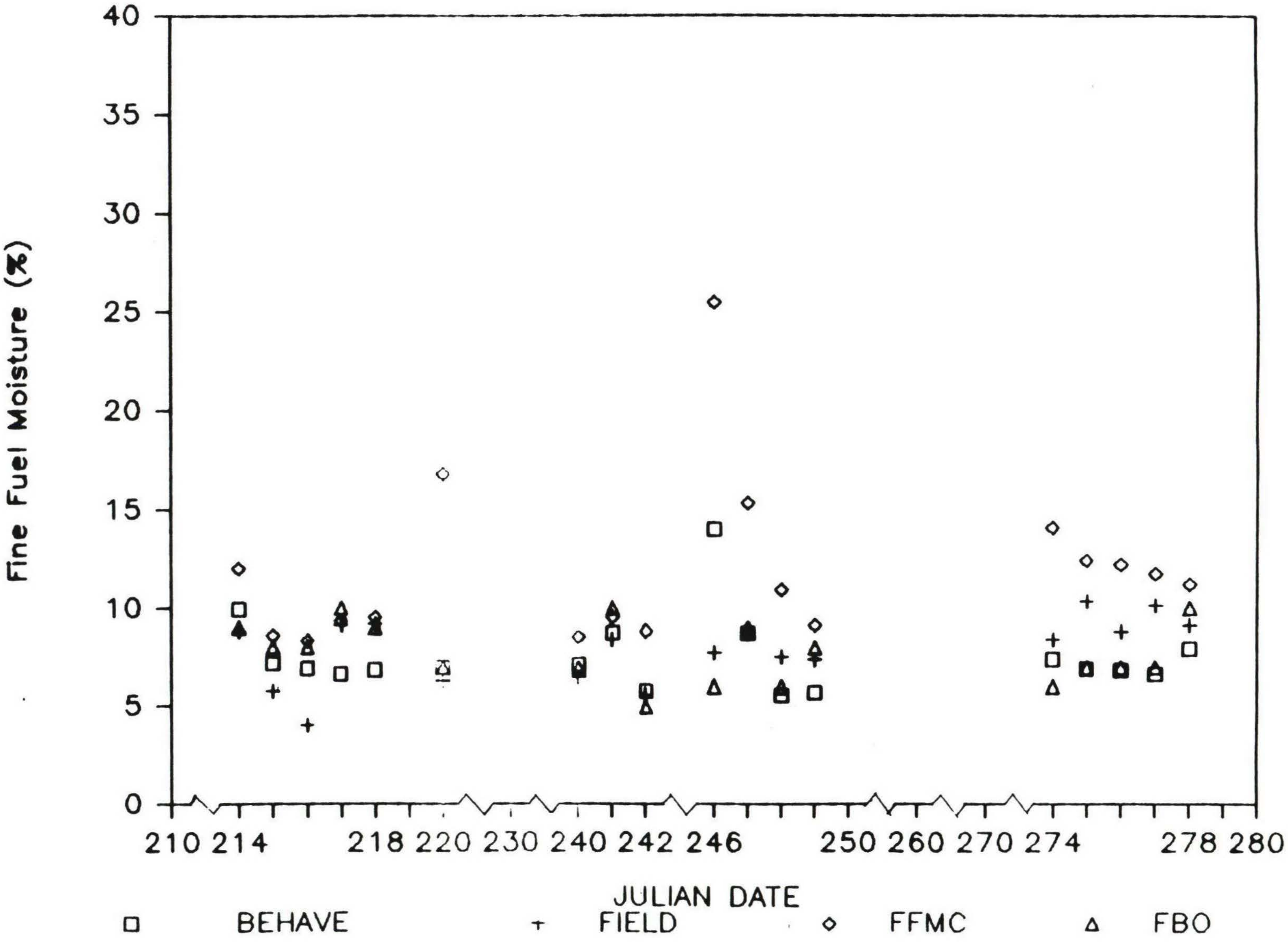


FIGURE 4: DAILY FFM (S. ASPECT, OPEN CANOPY, NEEDLE FUELS)

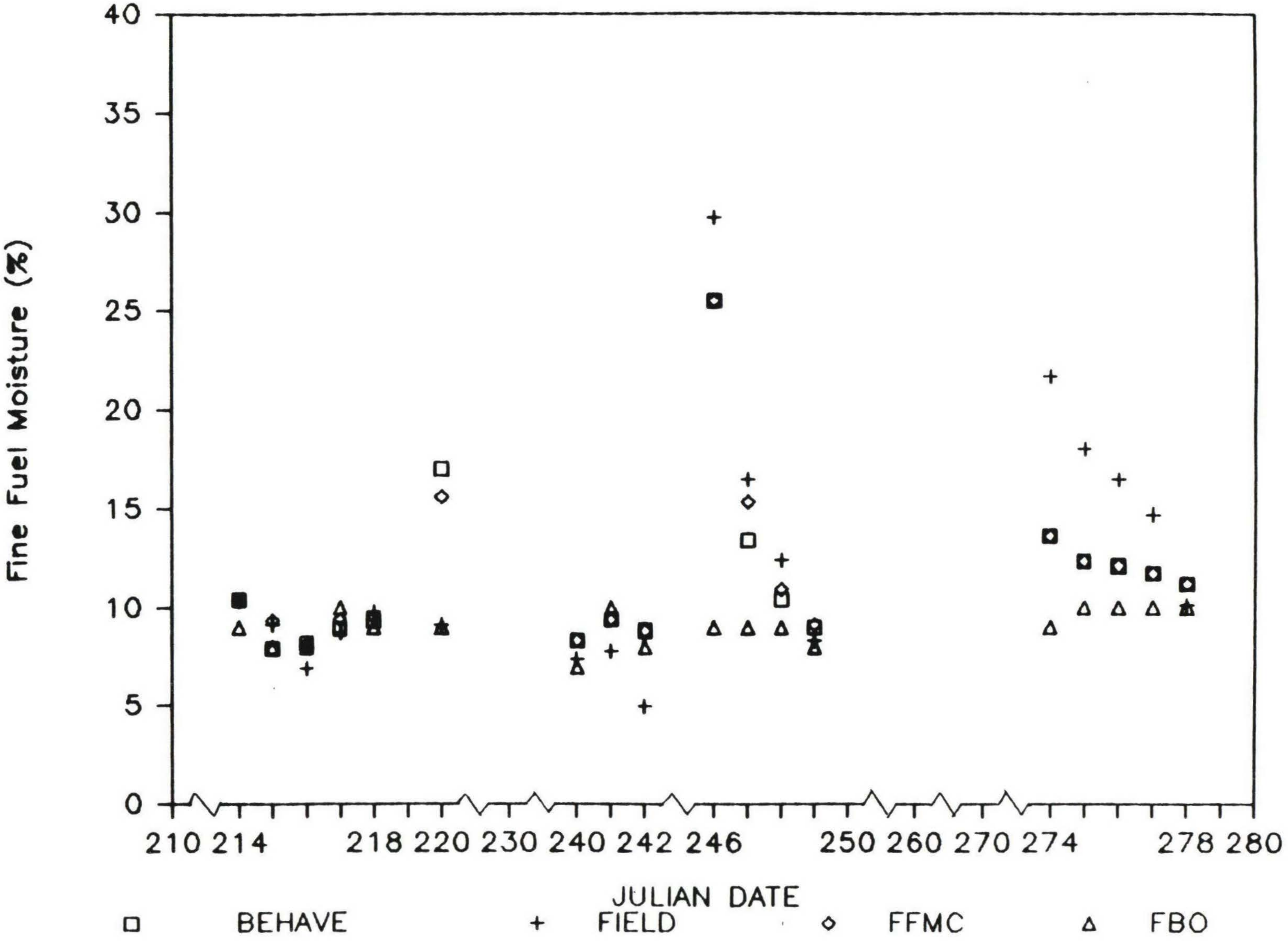


FIGURE 5: DAILY FFM (S. ASPECT, CLOSED CANOPY, GRASS FUELS)

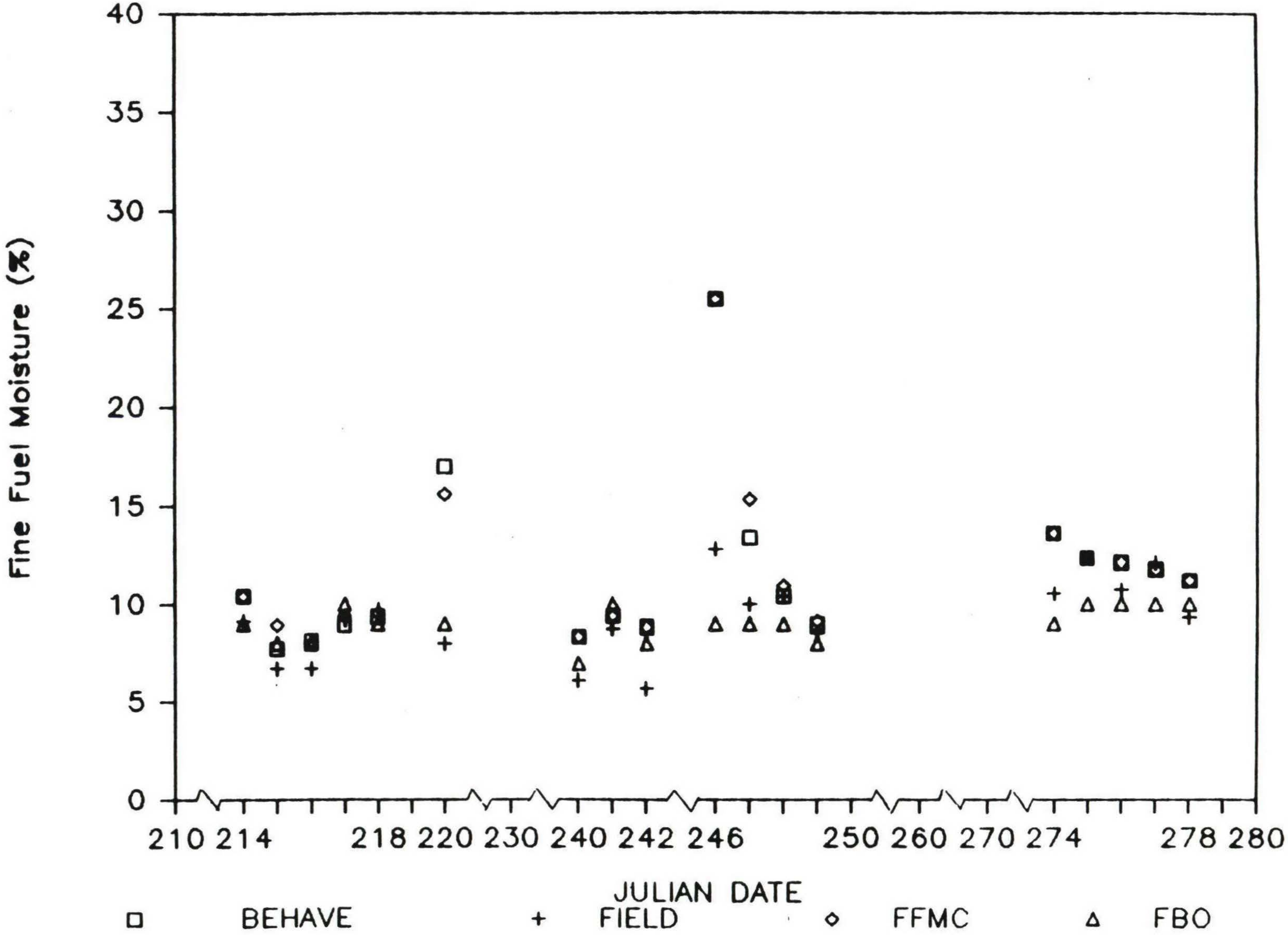


FIGURE 6: DAILY FFM (S. ASPECT, CLOSED CANOPY, NEEDLE FUEL)

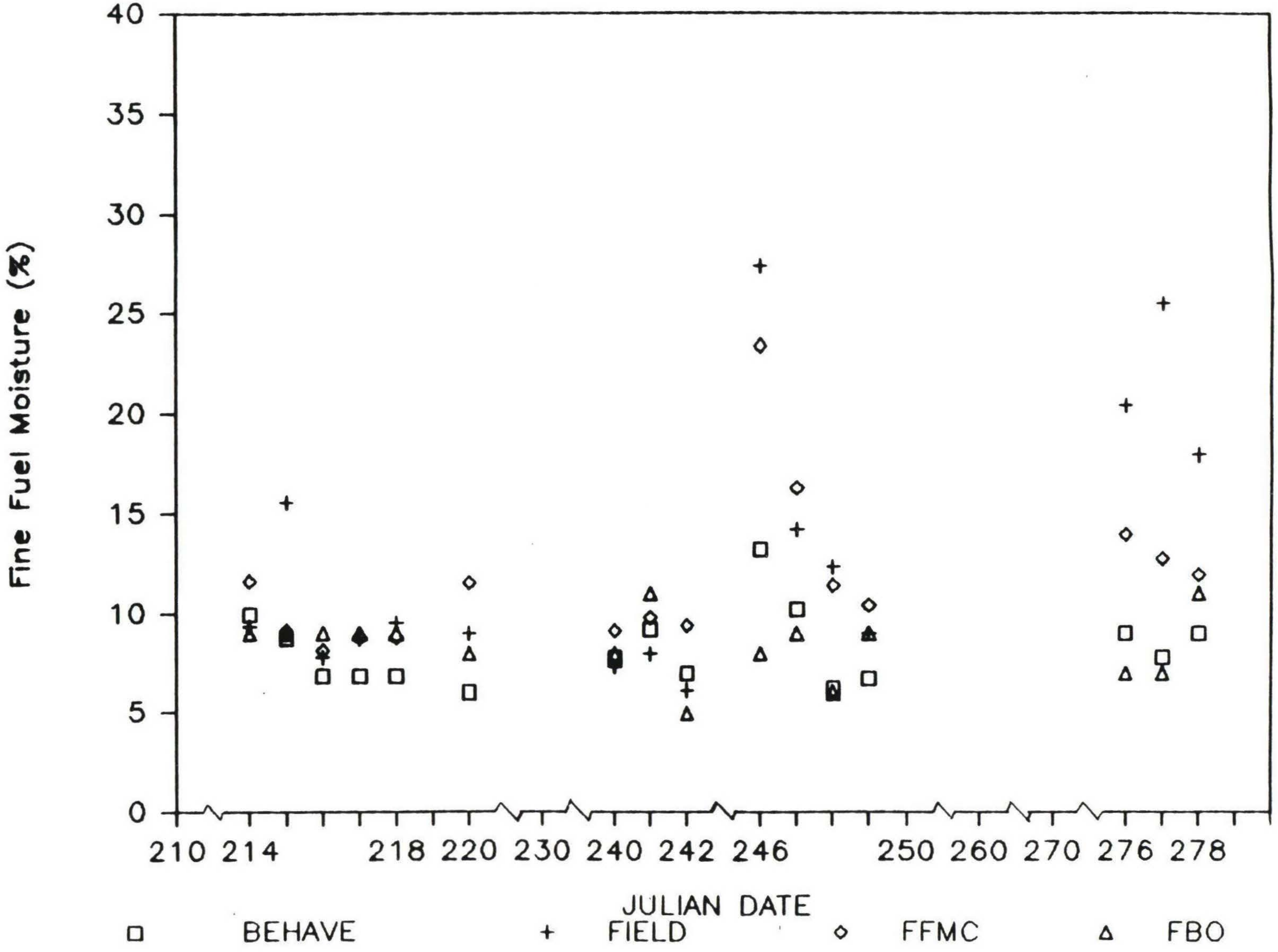


FIGURE 7: DAILY FFM (N. ASPECT, OPEN CANOPY, GRASS FUELS)

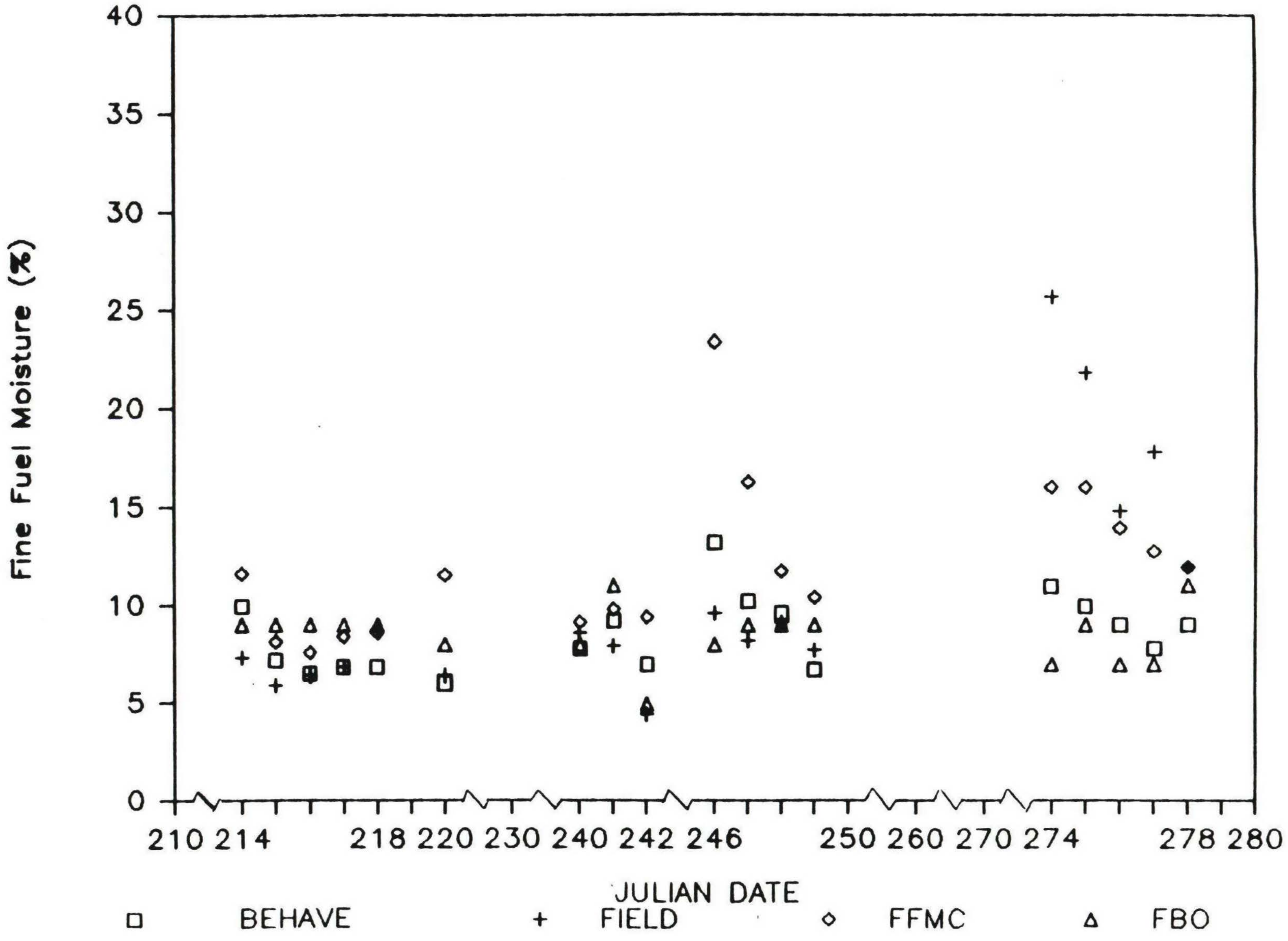


FIGURE 8: DAILY FFM (N. ASPECT, OPEN CANOPY, NEEDLE FUELS)

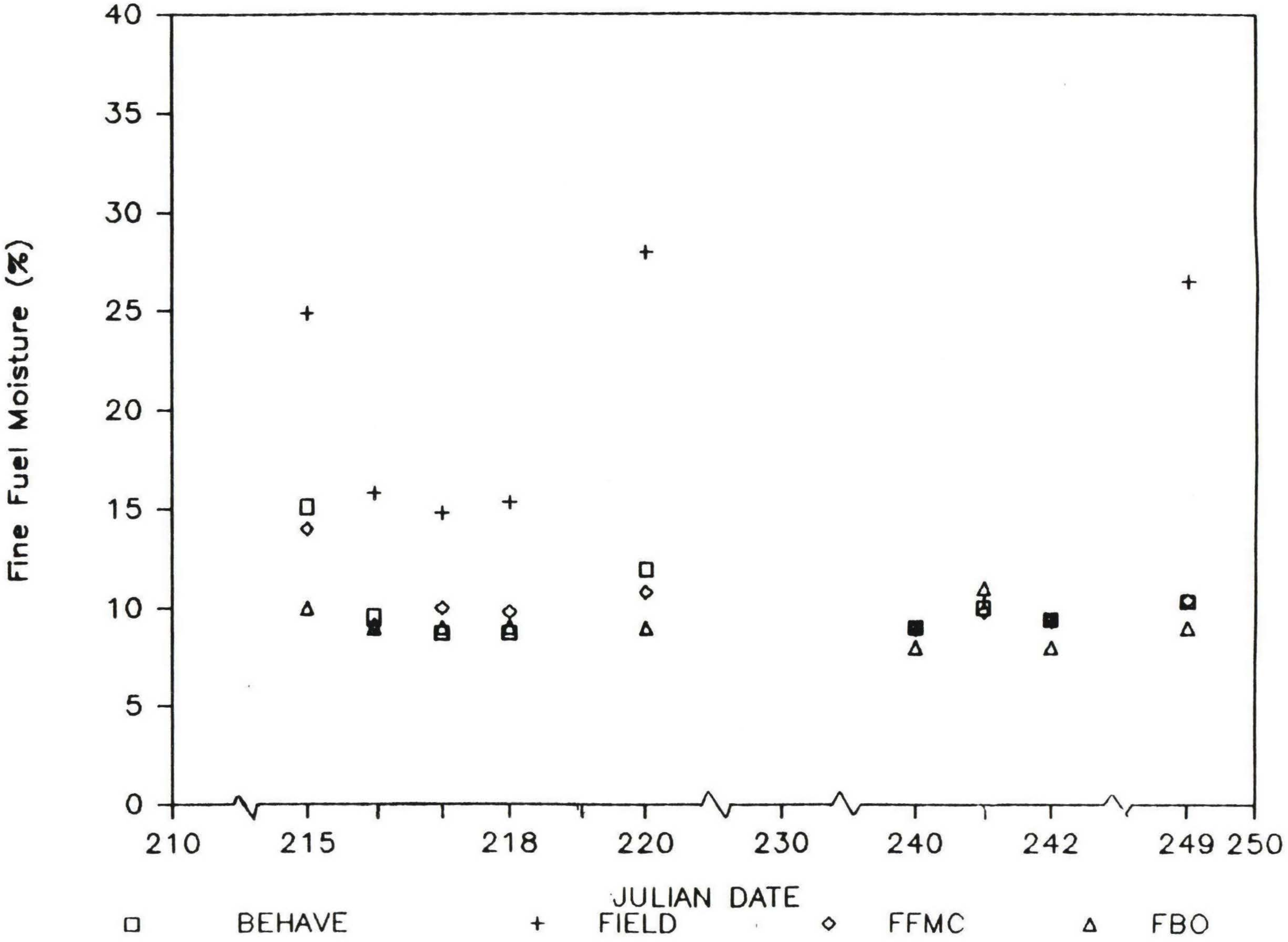


FIGURE 9: DAILY FFM (N. ASPECT, CLOSED CANOPY, GRASS FUELS)

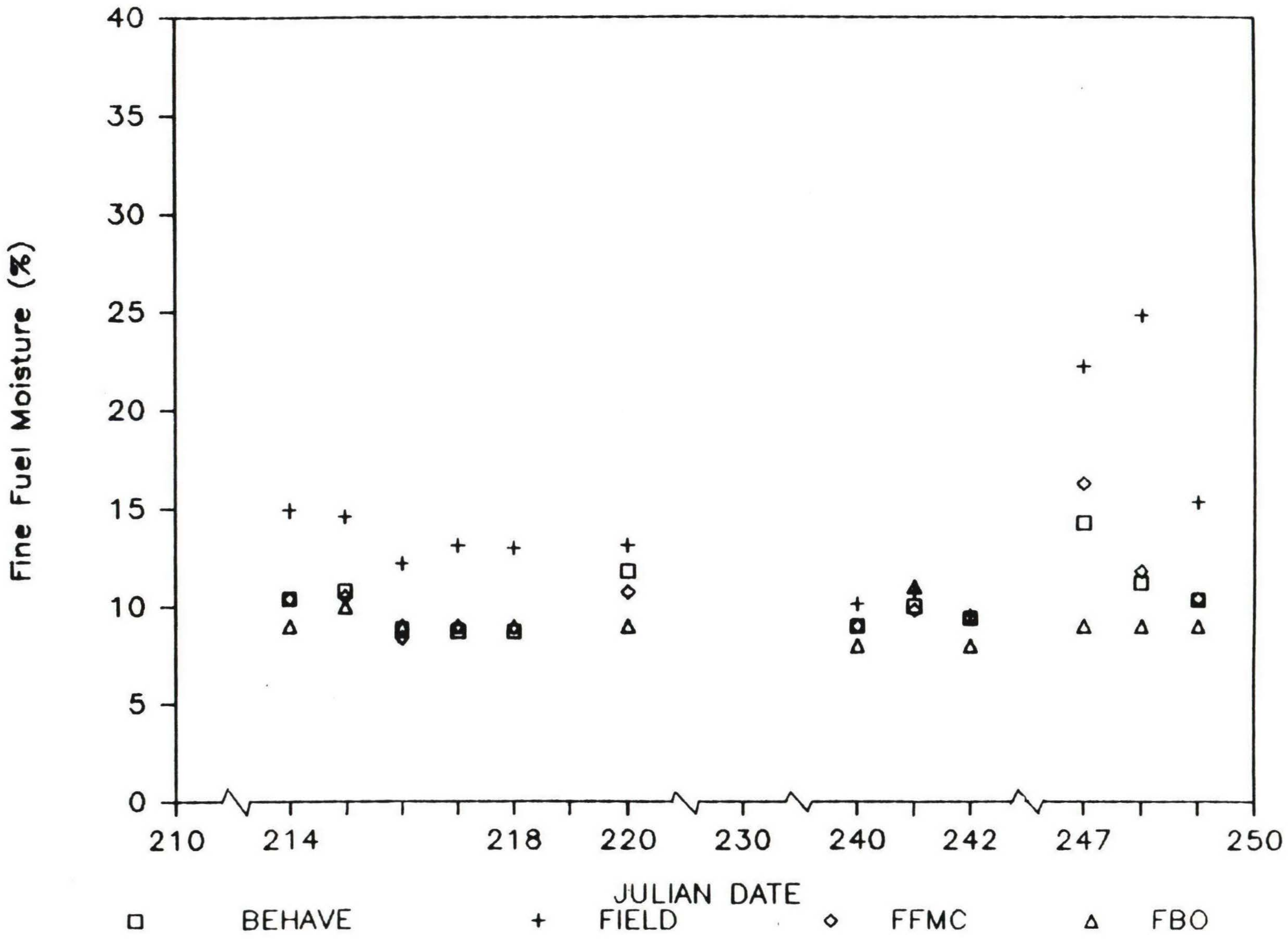


FIGURE 10: DAILY FFM (N.ASPECT, CLOSED CANOPY, NEEDLE FUEL)

TABLE 4: T-TEST RESULTS FOR DAILY FFM PREDICTIONS BY DATE, MODEL, AND SITE CONDITION

DATE	MODEL	SITE CONDITION+							
		SOG	SON	SCG	SCN	NOG	NON	NCG	NCN
8/1	BEHAVE		*		*		*	x	*
	FFMC	*	*	*	*	*	*	x	*
	FBO						*	x	*
8/2	BEHAVE		*		*		*	*	*
	FFMC		*		*		*	*	*
	FBO		*		*		*	*	*
8/3	BEHAVE	*	*	*	*	*		*	*
	FFMC	*	*	*	*		*	*	*
	FBO	*	*	*	*	*	*	*	*
8/4	BEHAVE	*	*			*		*	*
	FFMC						*	*	*
	FBO		*	*			*	*	*
8/5	BEHAVE	*	*			*	*	*	*
	FFMC	*				*		*	*
	FBO	*			*	*		*	*
8/7	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
	FBO	*	*		*	*	*	*	*
8/27	BEHAVE	*	*	*	*		*		*
	FFMC	*	*	*	*	*	*		*
	FBO	*	*		*	*	*	*	*
8/28	BEHAVE			*	*	*	*		*
	FFMC	*	*	*	*	*	*		*
	FBO	*	*	*	*	*	*	*	
8/29	BEHAVE	*		*	*	*	*		
	FFMC	*	*	*	*	*	*		
	FBO			*	*	*		*	*
9/2	BEHAVE	*	*		*	*	*	x	x
	FFMC	*	*		*		*	x	x
	FBO	*	*	*		*	*	x	x

*Significant at P>=.05.
xData unavailable for these treatments.
+Named by aspect, canopy condition, and fuel.
(Ex.:SOG=South aspect, Open canopy, Grass fuel).

TABLE 4: (CONTINUED)

DATE	MODEL	SITE CONDITION+							
		SOG	SON	SCG	SCN	NOG	NON	NCG	NCN
9/3	BEHAVE	*			*	*	*	x	*
	FFMC	*	*		*		*	x	*
	FBO	*		*		*	*	x	*
9/4	BEHAVE	*	*	*		*		x	*
	FFMC	*	*				*	x	*
	FBO	*	*	*		*		x	*
9/5	BEHAVE	*	*			*	*	*	*
	FFMC	*	*	*			*	*	*
	FBO	*	*				*	*	*
9/30	BEHAVE	*	*		*	x	*	x	x
	FFMC	*	*		*	x	*	x	x
	FBO	*	*	*		x	*	x	x
10/1	BEHAVE	*	*	*		x	*	x	x
	FFMC	*	*	*		x		x	x
	FBO	*	*	*	*	x	*	x	x
10/2	BEHAVE	*	*	*		*	*	x	x
	FFMC	*	*	*		*		x	x
	FBO	*		*	*	*	*	x	x
10/3	BEHAVE	*	*	*	*	*	*	x	x
	FFMC	*	*	*	*	*	*	x	x
	FBO	*	*	*		*	*	x	x
10/4	BEHAVE	*	*	*		*	*	x	x
	FFMC	*	*	*		*		x	x
	FBO	*	*	*		*	*	x	x

*Significant at P>=.05.
xData unavailable for these treatments.
+Named by aspect, canopy closure, and fuel.
(Ex.:SOG=South aspect, Closed canopy, Grass fuels).

FIGURE 11: FREQ. DISTR. OF RAE FOR BEHAVE DAILY PREDICTIONS

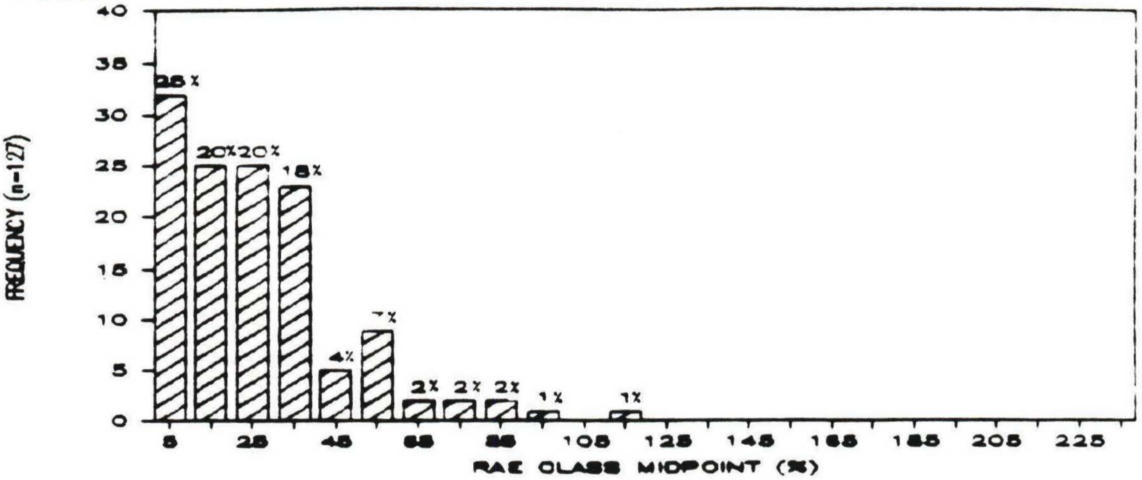


FIGURE 12: FREQ. DISTR. OF RAE FOR FFMC DAILY PREDICTIONS

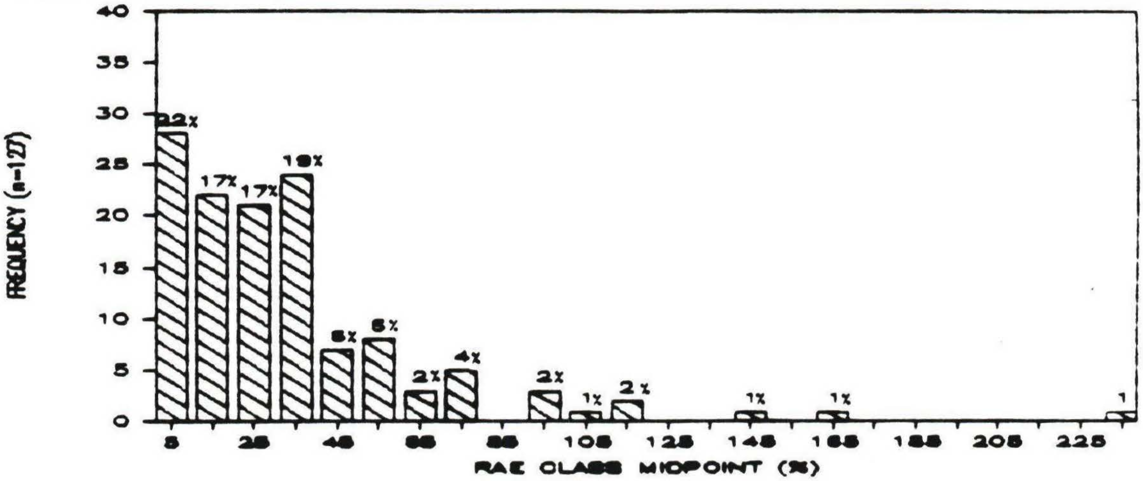


FIGURE 13: FREQ. DISTR. OF RAE FOR FBO DAILY PREDICTIONS

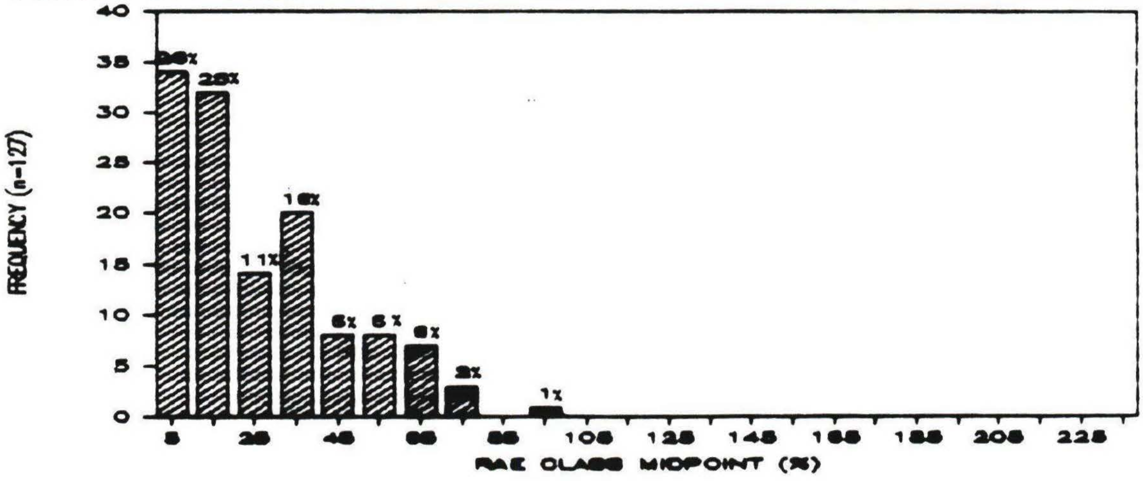


TABLE 5: MODEL PREFERENCE BY RAE CLASS AND SITE CONDITION FOR DAILY PREDICTIONS

SITE CONDITION+	PERCENTAGE OF ESTIMATES WITHIN 20% RAE BEHAVE	FFMC	FBO
SOG	*50%	38%	50%
SON	44%	22%	*61%
SCG	61%	*61%	50%
SCN	56%	56%	*89%
NOG	32%	*44%	50%
NON	*39%	28%	44%
NCG	*33%	33%	33%
NCN	*33%	33%	17%

+Named by aspect, canopy closure, and fuel. Ex: SOG= South aspect, Open canopy, Grass fuels.
*Best predictive model for a particular site condition (based on frequency distribution within RAE classes).

TABLE 6: RAE ANALYSIS BY PERIOD LENGTH FOR DAILY FINE FUEL MOISTURE PREDICTIONS

PERIOD LENGTH	SAMPLE SIZE	PERCENTAGE OF ESTIMATES WITHIN 20% RAE BEHAVE	FFMC	FBO
1-2 days	30	*40%	27%	40%
3 days	35	49%	40%	*57%
4-7 days	57	51%	51%	*58%

*Best predictive model for a particular period length (based on frequency distribution within RAE classes).

TABLE 7: RAE ANALYSIS BY TIME OF YEAR FOR DAILY PREDICTIONS

TIME OF YEAR	SAMPLE SIZE	PERCENTAGE OF ESTIMATES WITHIN 20% RAE BEHAVE	FFMC	FBO
8/1-8/7	47	45%	40%	*57%
8/27-9/5	52	54%	44%	*56%
9/30-10/4	28	29%	32%	*36%

*Best predictive model for a particular time of year (based on frequency distributions within RAE classes).

Diurnal Values

Field measurements and model estimates of diurnal fine fuel moisture are illustrated in Figures 14 through 29. The models did not differ greatly in their predictions; they were usually within 1% moisture of one another, and were never more than 2.5% apart. This is not surprising, since the major difference between the two diurnal models is that the BEHAVE model estimates hourly weather, while the FFMC requires it as input (Rothermel et al. 1986).

Two-tailed t-tests run for each hour on the two diurnal cycles indicated that no model was able to predict diurnal fine fuel moisture more than half the time for any of the site conditions (see Tables 8 and 9). Although at some hours one or both models predicted accurately for certain site conditions, no clear pattern was evident throughout a twenty-four hour period. Models which predicted well at a particular time for a particular treatment on one diurnal cycle did not necessarily predict well at the same time for the same treatment on the other diurnal cycle.

Results of analysis of diurnal model predictions by the RAE method are shown in Figures 30 and 31. The frequency distributions of diurnal predictions are much less skewed than those of daily estimates (Figures 11-13), indicating less accuracy of prediction for the diurnal

FIGURE 14: DIURNAL FFM, 8/18/84 (S. ASPECT, OPEN CANOPY, GRASS FUELS)

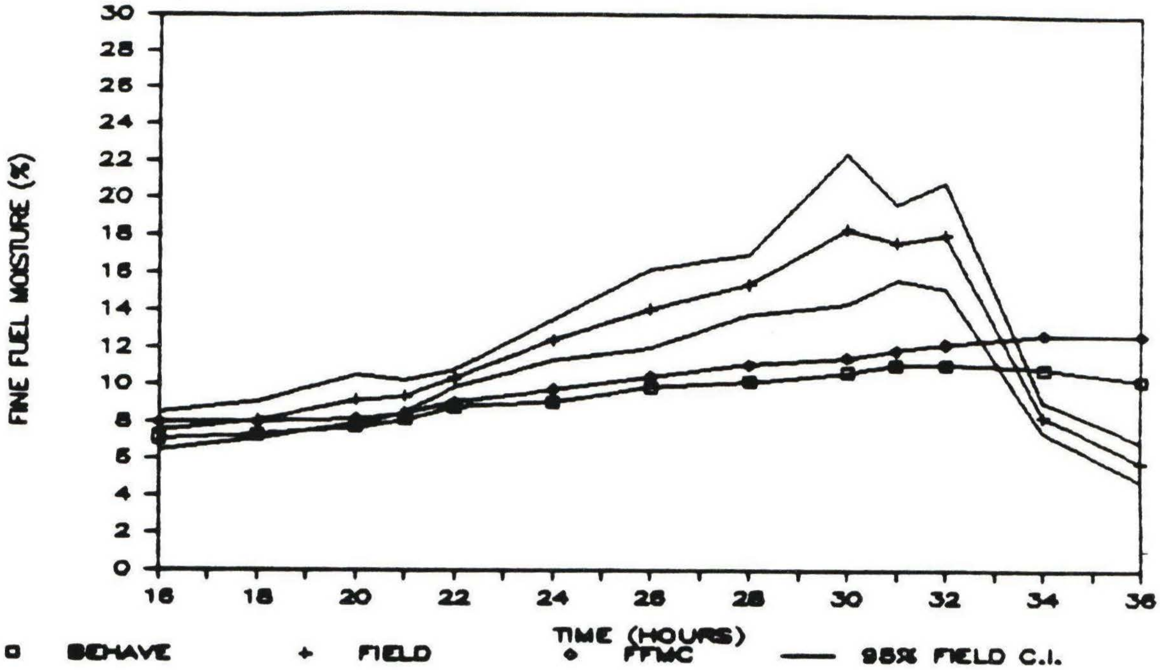


FIGURE 15: DIURNAL FFM, 8/18/84 (S. ASPECT, OPEN CANOPY, NEEDLE FUELS)

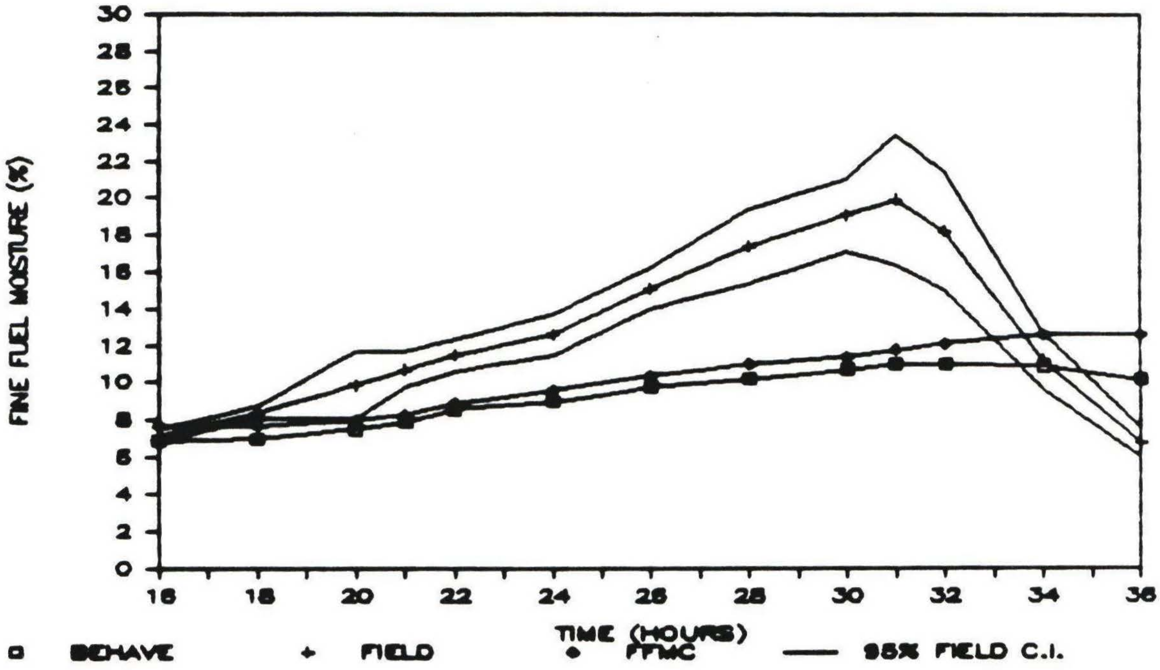


FIGURE 16: DIURNAL FFM, 8/18/84 (S. ASPECT, CLOSED CANOPY, GRASS FUELS)

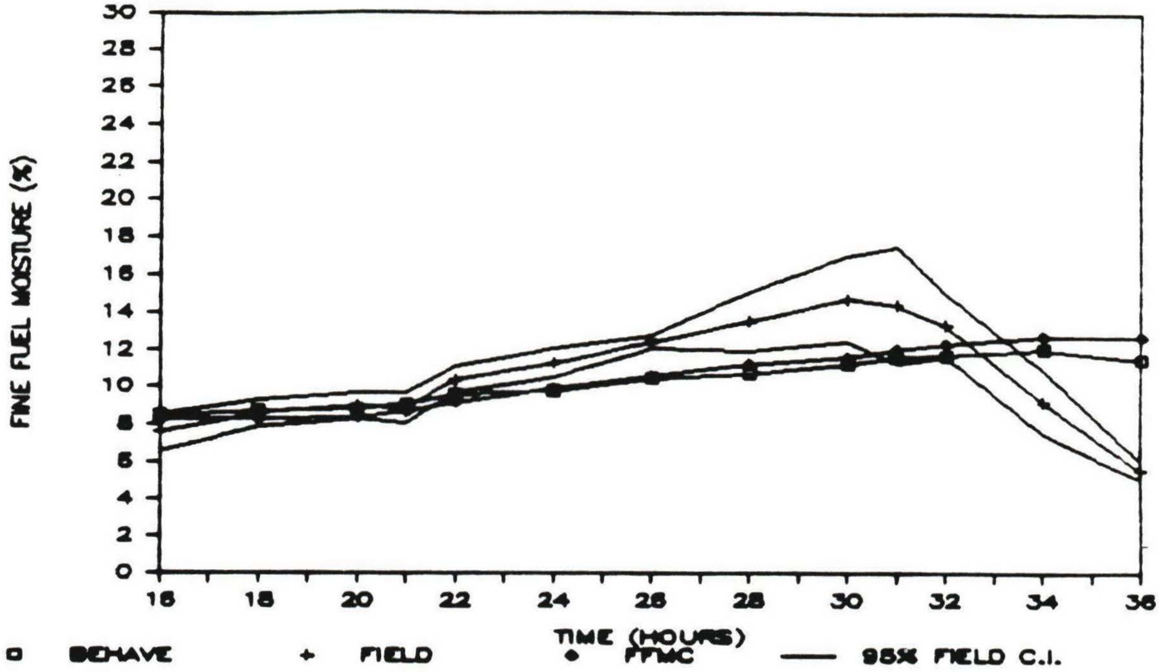


FIGURE 17: DIURNAL FFM, 8/18/84 (S. ASPECT, CLOSED CANOPY, NEEDLE FUELS)

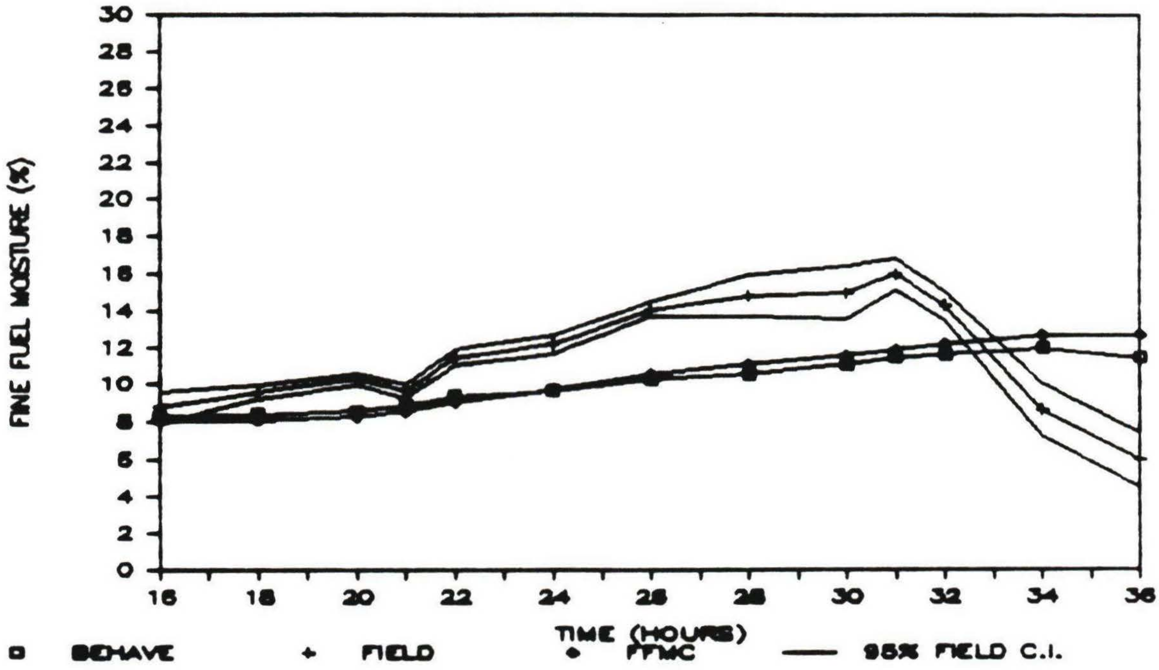


FIGURE 18: DIURNAL FFM, 8/18/84 (N. ASPECT, OPEN CANOPY, GRASS FUELS)

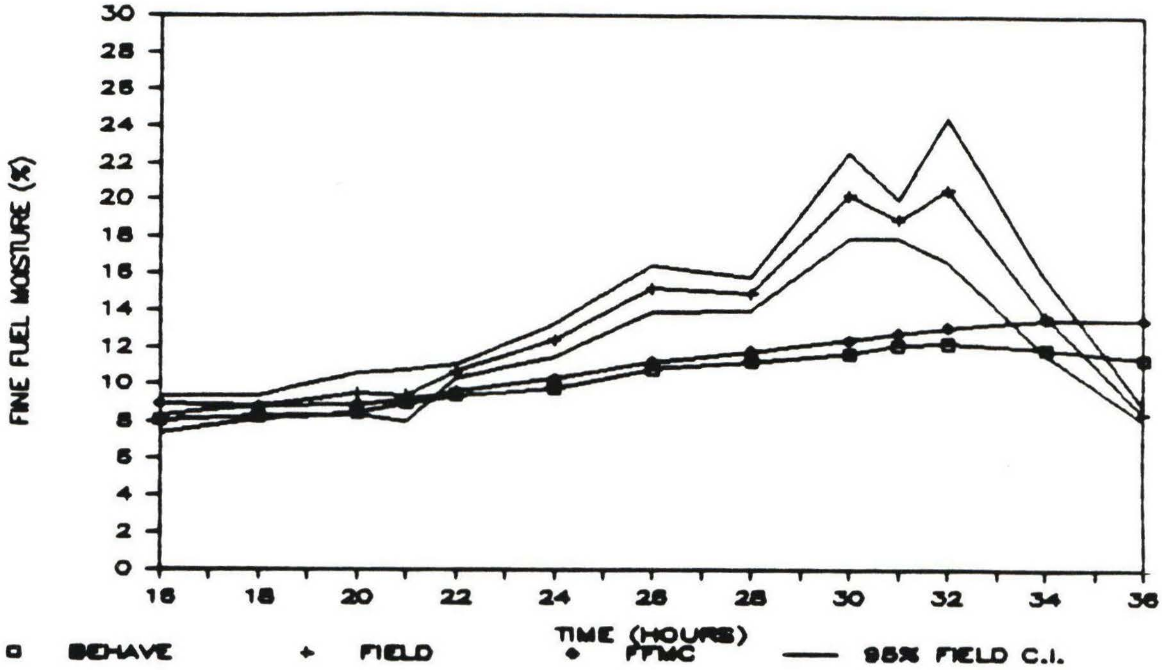


FIGURE 19: DIURNAL FFM, 8/18/84 (N. ASPECT, OPEN CANOPY, NEEDLE FUELS)

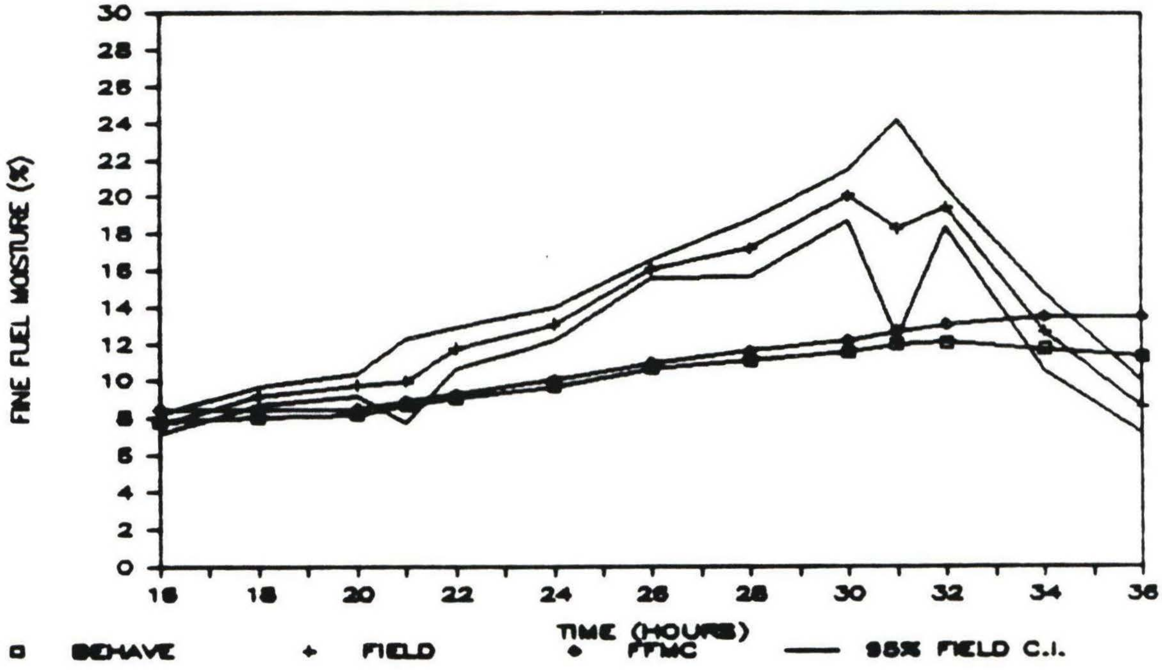


FIGURE 20: DIURNAL FFM, 8/18/84 (N. ASPECT, CLOSED CANOPY, GRASS FUELS)

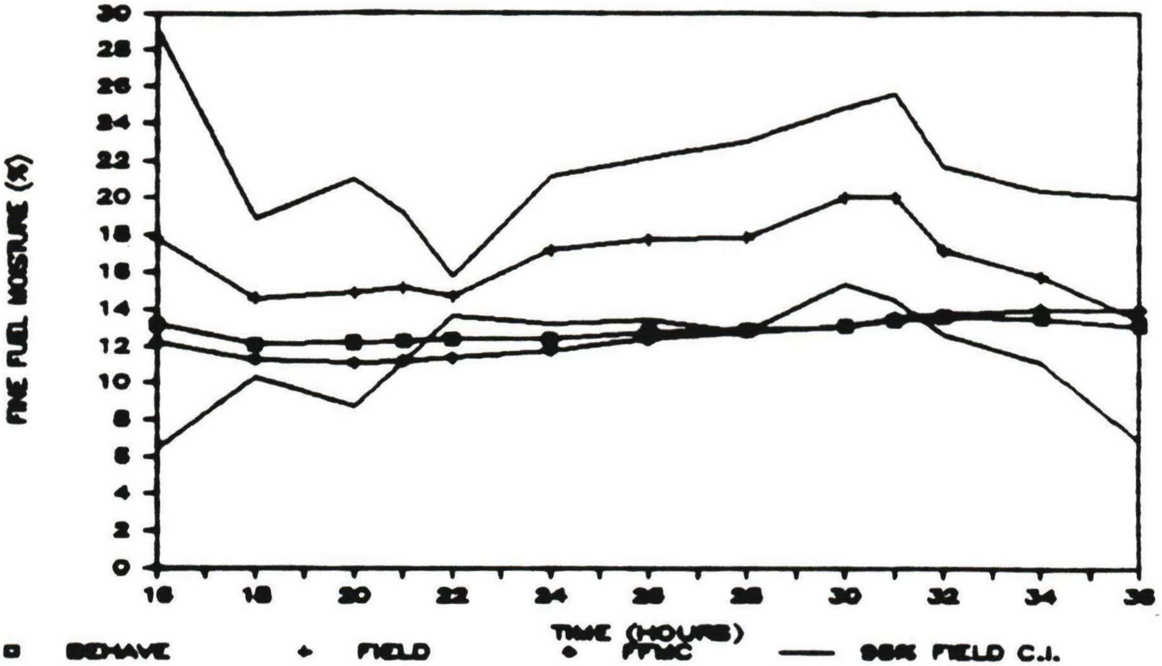


FIGURE 21: DIURNAL FFM, 8/18/84 (N. ASPECT, CLOSED CANOPY, NEEDLE FUELS)

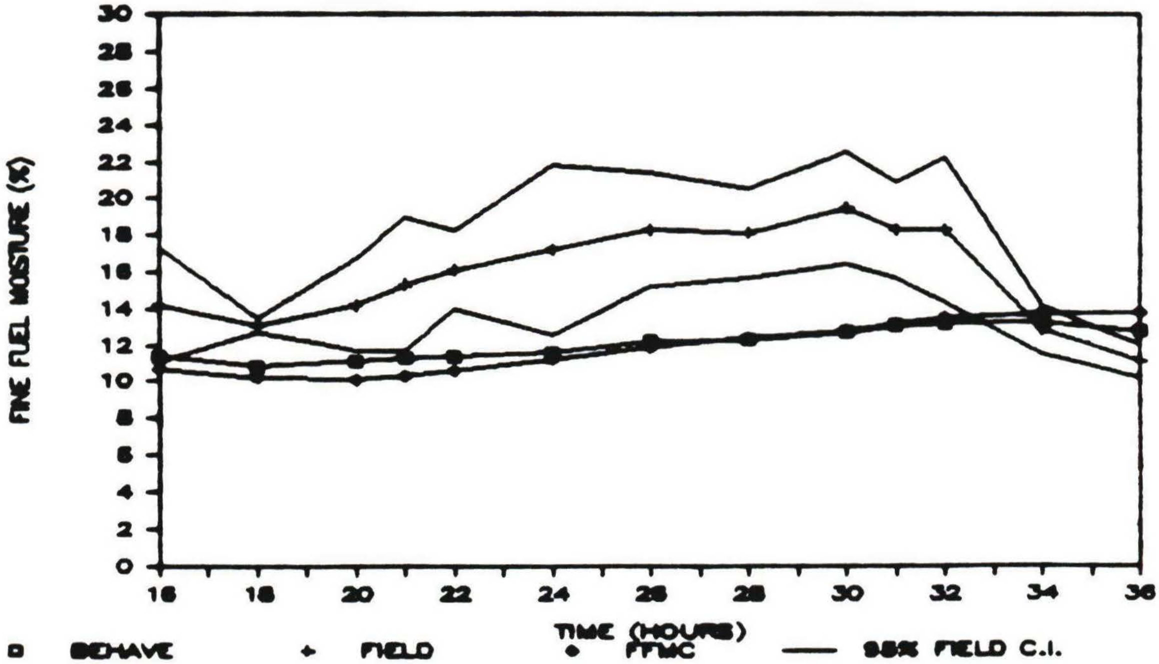


FIGURE 22: DIURNAL FFM, 8/25/84 (S. ASPECT, OPEN CANOPY, GRASS FUELS)

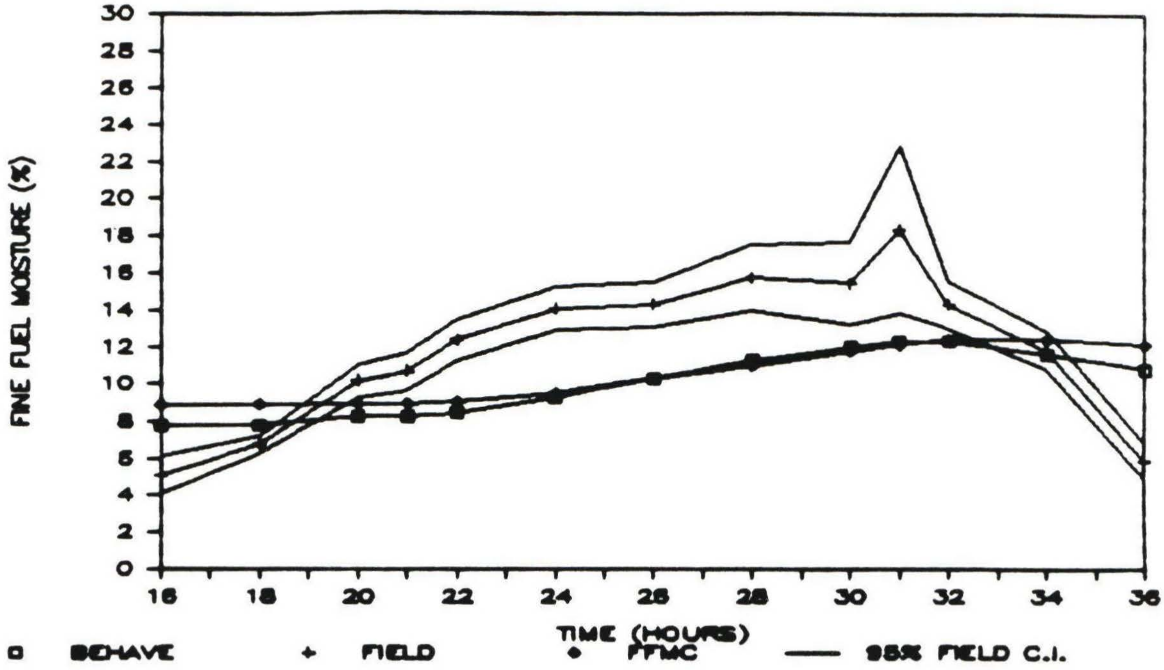


FIGURE 23: DIURNAL FFM, 8/25/84 (S. ASPECT, OPEN CANOPY, NEEDLE FUELS)

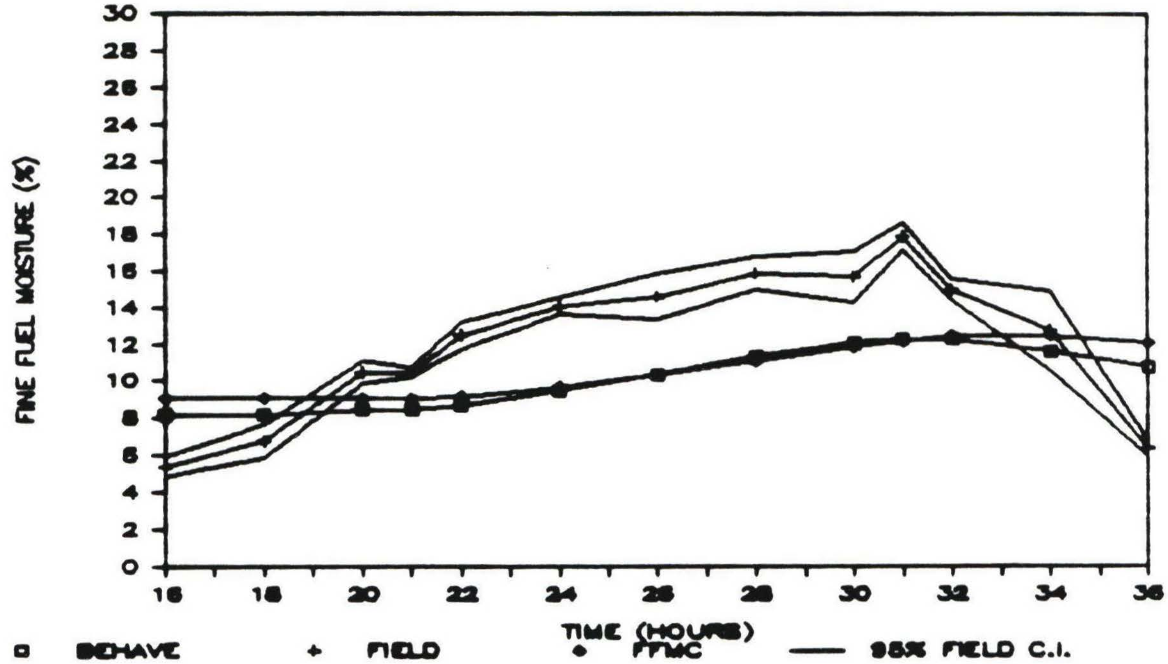


FIGURE 24: DIURNAL FFM, 8/25/84 (S. ASPECT, CLOSED CANOPY, GRASS FUELS)

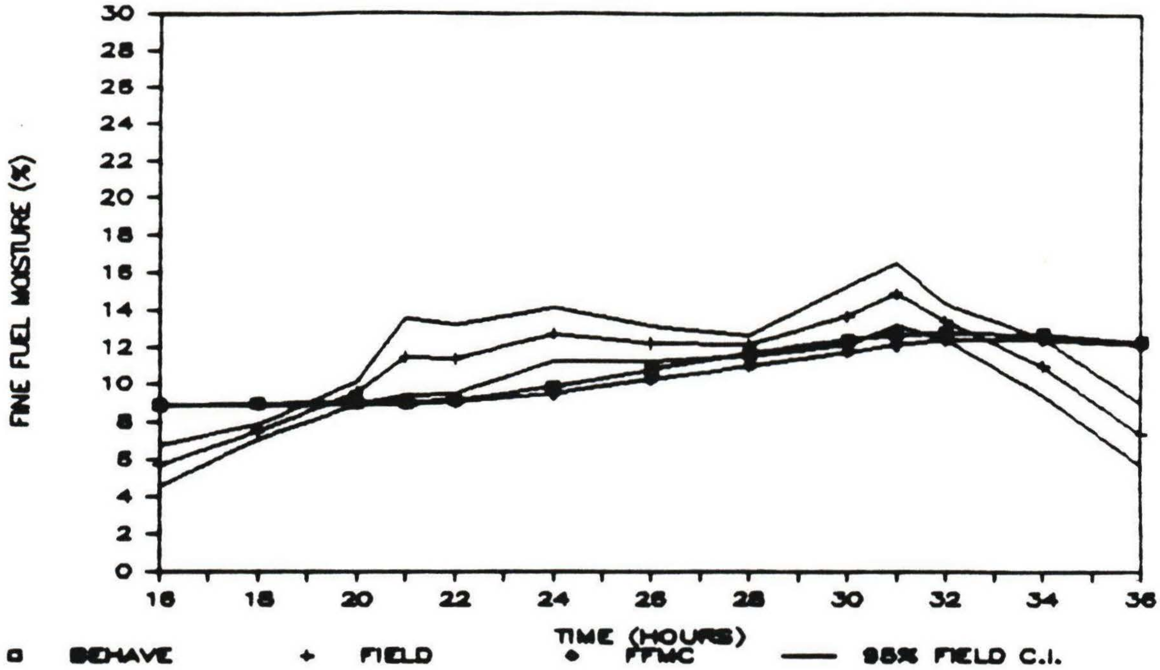


FIGURE 25: DIURNAL FFM, 8/25/84 (S. ASPECT, CLOSED CANOPY, NEEDLE FUELS)

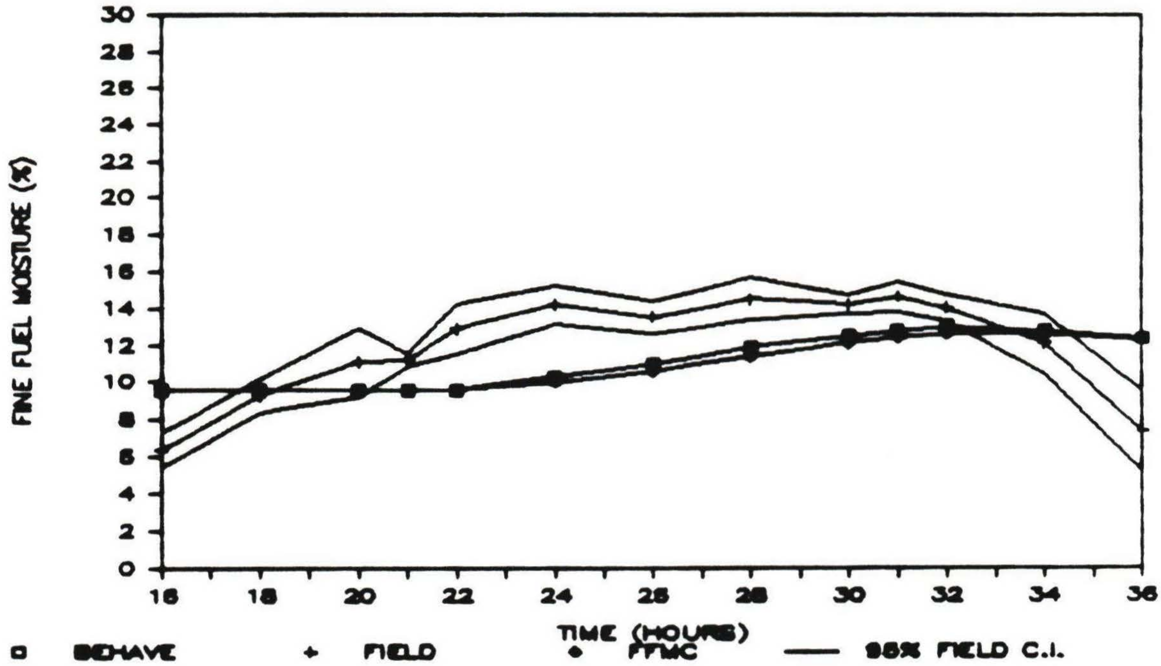


FIGURE 26: DIURNAL FFM, 8/25/84 (N. ASPECT, OPEN CANOPY, GRASS FUELS)

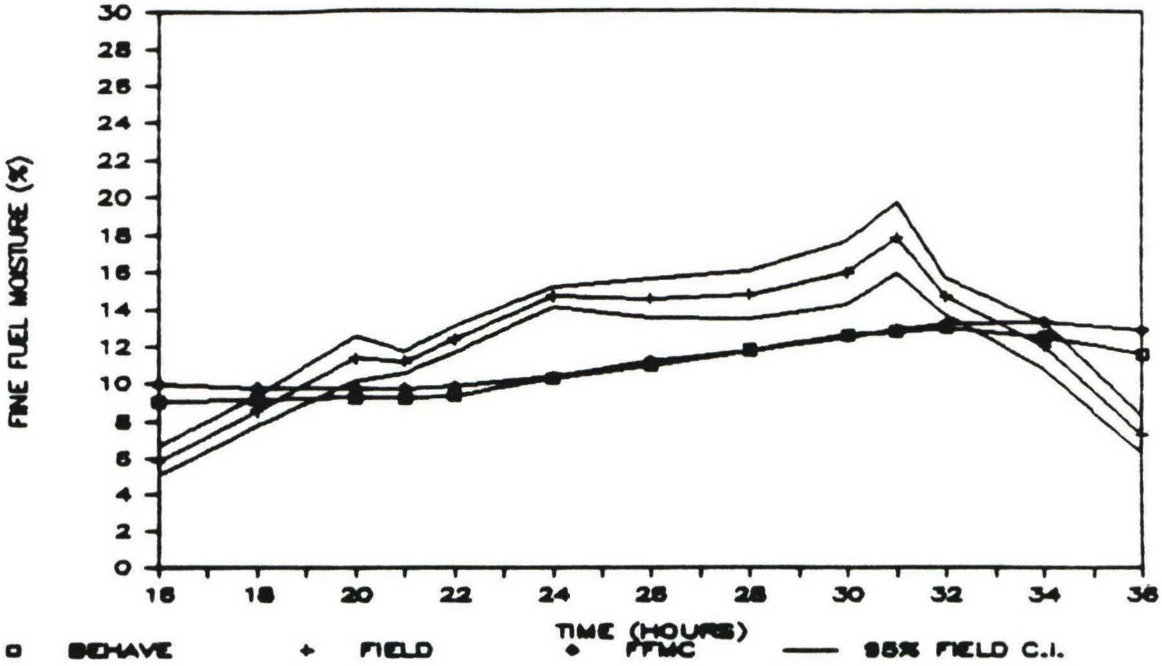


FIGURE 27: DIURNAL FFM, 8/25/84 (N. ASPECT, OPEN CANOPY, NEEDLE FUELS)

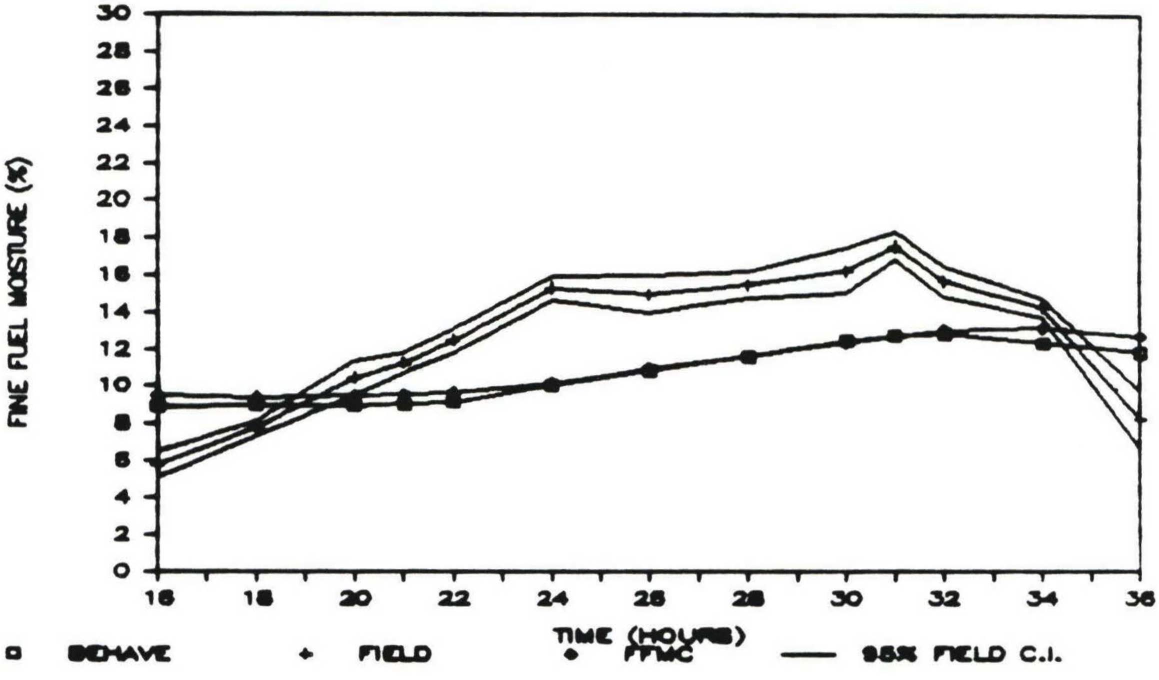


FIGURE 28: DIURNAL FFM, 8/25/84 (N. ASPECT, CLOSED CANOPY, GRASS FUELS)

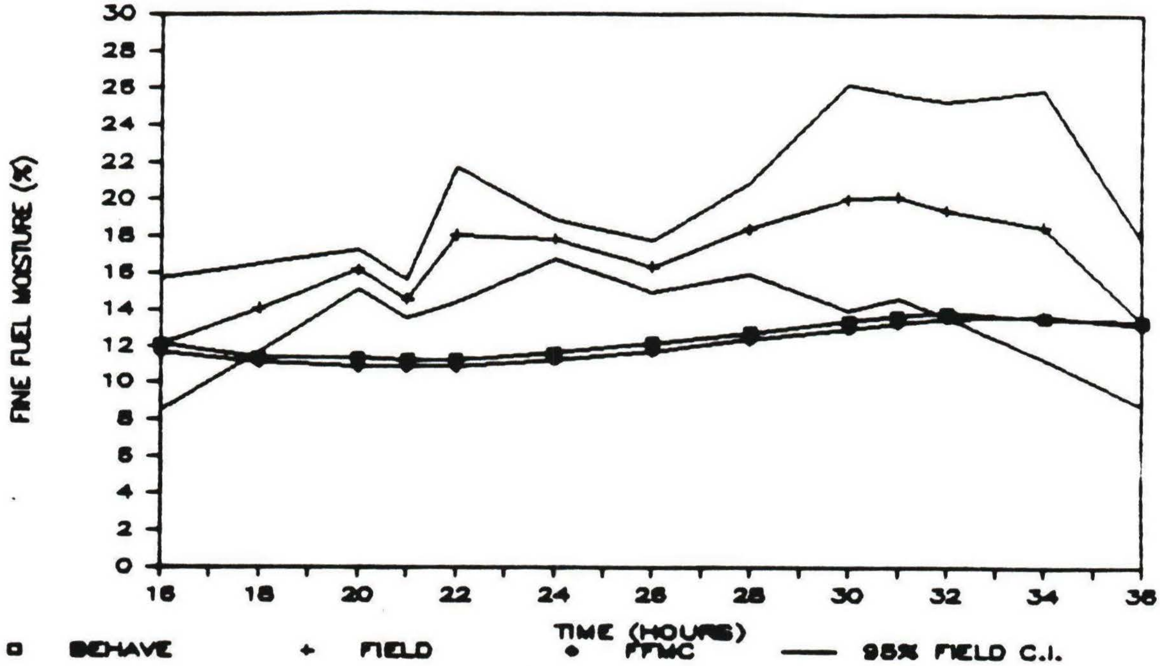


FIGURE 29: DIURNAL FFM, 8/25/84 (N. ASPECT, CLOSED CANOPY, NEEDLE FUELS)

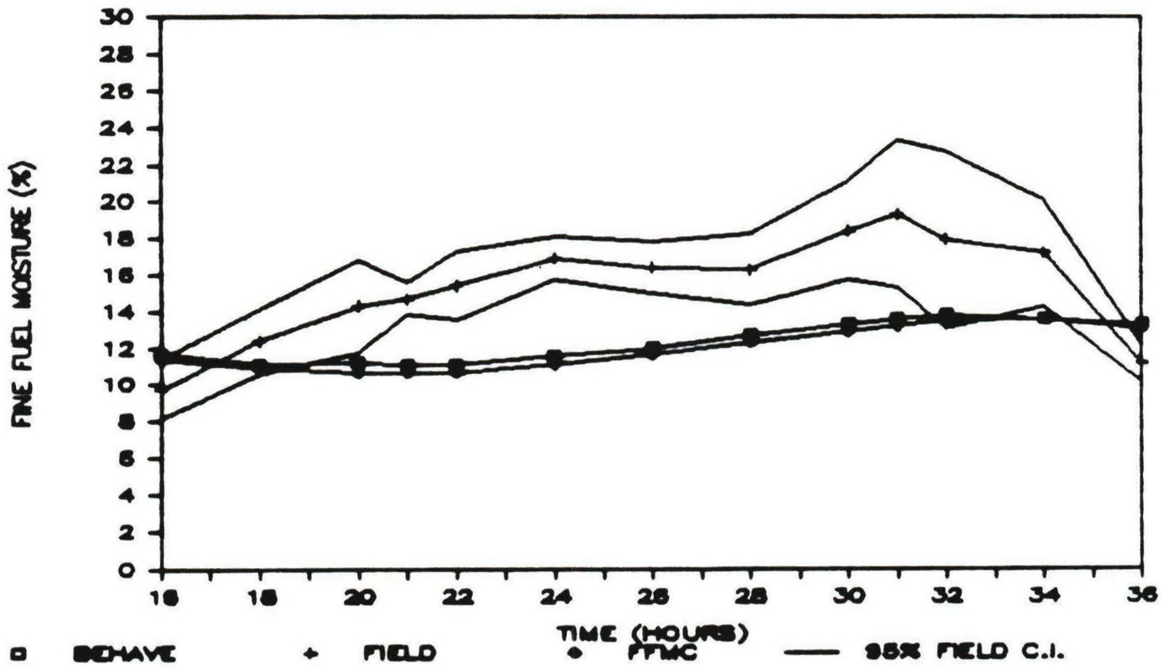


TABLE 8: T-TEST RESULTS FOR DIURNAL FFM PREDICTIONS, 8/18/84, BY TIME, MODEL, AND SITE CONDITION

TIME (HRS)++	MODEL	SITE CONDITION+ SOG	SON	SCG	SCN	NOG	NON	NCG	NCN
1600	BEHAVE								
	FFMC						*		*
1800	BEHAVE		*		*		*		*
	FFMC		*		*		*		*
2000	BEHAVE	*	*		*	*	*		*
	FFMC		*		*		*		*
2100	BEHAVE	*	*		*				*
	FFMC	*	*		*			*	*
2200	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2400	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2600	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2800	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
3000	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
3100	BEHAVE	*	*		*	*	*	*	*
	FFMC	*	*		*	*		*	*
3200	BEHAVE	*	*		*	*	*		*
	FFMC	*	*		*	*	*		*
3400	BEHAVE	*		*	*				
	FFMC	*		*	*				
3600	BEHAVE	*	*	*	*	*	*		*
	FFMC	*	*	*	*	*	*		*

*Significant at P>=.05
+Named by aspect, canopy condition, and fuel. Ex: SOG= South aspect, Open canopy, Grass fuel.
++Time expressed as military time, but continuing through til noon of next day (Ex: 2400=midnight, 2600=2:00 am).

TABLE 9: T-TEST RESULTS FOR DIURNAL FFM PREDICTIONS, 8/25/84, BY TIME, MODEL AND SITE CONDITION

TIME (HRS)++	MODEL	SITE CONDITION+ SOG	SON	SCG	SCN	NOG	NON	NCG	NCN
1600	BEHAVE	*	*	*	*	*	*		*
	FFMC	*	*	*	*	*	*		
1800	BEHAVE	*	*	*			*	*	
	FFMC	*	*	*		*	*	*	
2000	BEHAVE	*	*			*	*	*	*
	FFMC	*	*	*		*	*	*	*
2100	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2200	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2400	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2600	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
2800	BEHAVE	*	*		*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
3000	BEHAVE	*	*		*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
3100	BEHAVE	*	*	*	*	*	*	*	*
	FFMC	*	*	*	*	*	*	*	*
3200	BEHAVE	*	*		*	*	*		
	FFMC	*	*	*	*	*	*	*	
3400	BEHAVE			*			*		*
	FFMC					*	*		*
3600	BEHAVE	*	*	*	*	*	*		*
	FFMC	*	*	*	*	*	*		*

*Significant at P>=.05
+Named by aspect, canopy condition, and fuel.
(Ex.:SOG=South aspect, Open canopy, Grass fuels.)
++Time expressed as military time, but continuing through til noon of next day (Ex:2400=midnight, 2600=2:00 am).

FIGURE 30: FREQUENCY DISTRIBUTION OF RAE FOR BEHAVE DIURNAL PREDICTIONS

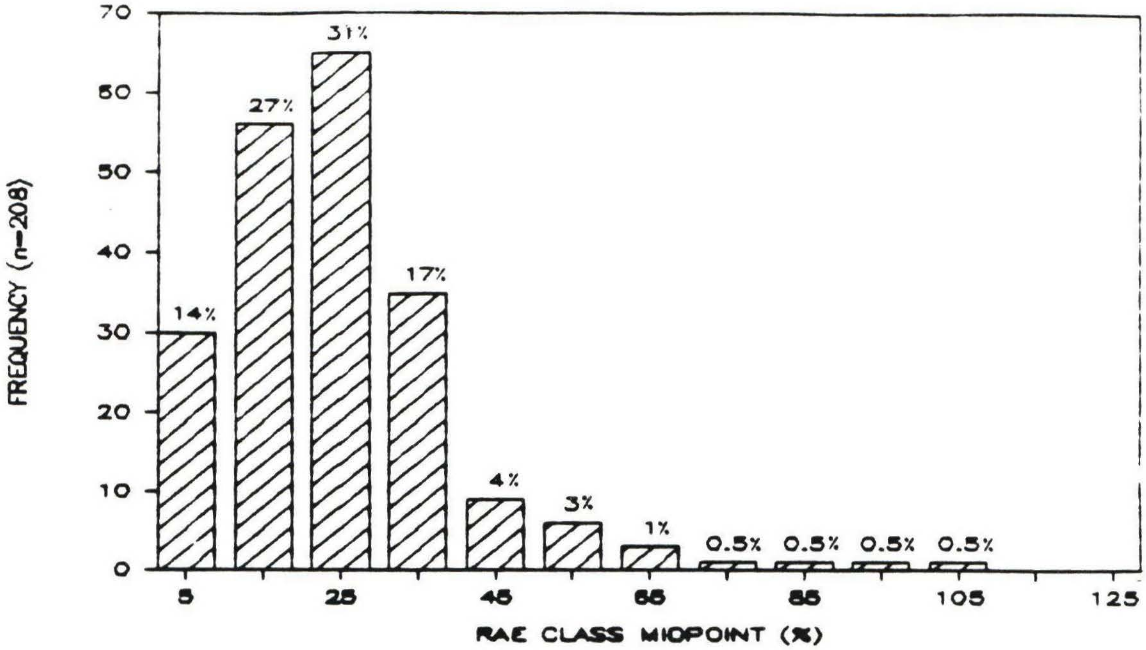
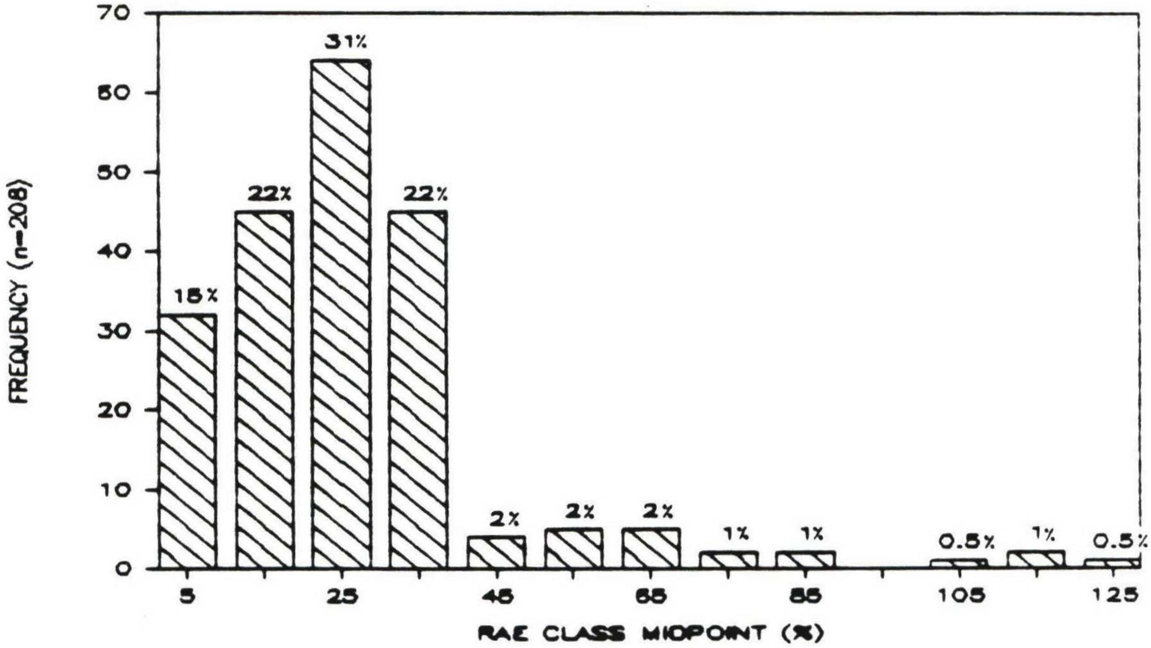


FIGURE 31: FREQUENCY DISTRIBUTION OF RAE FOR FFMC DIURNAL PREDICTIONS



estimates. Only 41% of the BEHAVE estimates and 37% of the FFMC estimates fell within 20% RAE of the observed fine fuel moisture.

Results of RAE analysis for diurnal model predictions are shown by site condition in Table 10. Both models predicted reasonably well for the two south aspect, closed canopied site conditions. On all other sites, both models showed too flat a diurnal response to imitate observed fine fuel moisture fluctuations very closely. The models did not respond quickly enough to nighttime conditions which caused the observed moisture to rise rapidly and steadily from late afternoon through sunrise, and to morning conditions which caused a rapid decrease in observed moisture from sunrise through noon. Consequently, most predicted values fell below observed values.

TABLE 10: RAE ANALYSIS BY SITE CONDITION FOR DIURNAL FINE FUEL MOISTURE PREDICTIONS

SITE CONDITION+	PERCENTAGE OF PREDICTIONS WITHIN 20% RAE	
	BEHAVE	FFMC
SOG	*35%	34%
SON	27%	*31%
SCG	*69%	69%
SCN	*57%	50%
NOG	42%	*46%
NON	39%	*50%
NCG	*35%	16%
NCN	*27%	16%

+Site conditions are named by aspect, canopy, and fuel conditions (ex:SOG=South aspect, Open canopy, Grass fuel).
*Best predictive model (criteria based on frequency distribution within RAE classes).

Table 11 provides a comparison of the diurnal temperature and relative humidity values estimated by BEHAVE with the actual temperature and relative humidity values for the two twenty-four hour periods. The model was given actual weather values for 2:00 p.m., sunset, sunrise, and 12:00 noon, from which it generated estimates for every other hour. BEHAVE's temperature estimates were very good; they were usually within 2.5 degrees of the actual temperatures. Relative humidity estimates were also good, averaging about 4% from actual measurements.

TABLE 11: DIURNAL TEMP. AND R.H., MEASURED VS BEHAVE VALUES

DATE	TIME (HRS)	SOUTH ASPECT TEMP (F) ACTUAL	SOUTH ASPECT TEMP (F) EST.	SOUTH ASPECT RH (%) ACTUAL	SOUTH ASPECT RH (%) EST.	NORTH ASPECT TEMP (F) ACTUAL	NORTH ASPECT TEMP (F) EST.	NORTH ASPECT RH (%) ACTUAL	NORTH ASPECT RH (%) EST.
8/18	1400	79	79	32	32	74	74	36	36
	1500	82	79	26	32	83	74	30	36
	1600	82	78	26	32	85	75	29	36
	1700	80	77	27	33	83	75	30	36
	1800	77	76	28	33	82	76	30	36
	1900	74	74	34	34	77	77	36	36
	2000	67	71	37	37	74	74	38	39
	2100	66	69	45	40	66	71	49	42
	2200	63	66	54	42	64	98	54	45
	2300	62	64	51	45	62	65	54	48
	2400	61	62	51	47	62	63	53	50
	2500	59	60	56	49	59	61	60	52
	2600	59	59	56	50	58	59	60	54
	2700	58	58	54	51	58	58	58	55
	2800	58	57	53	52	57	57	57	56
	2900	57	57	52	52	57	57	56	56
	3000	56	57	55	52	56	57	58	56
	3100	54	58	63	51	53	58	65	55
	3200	56	59	60	49	54	59	64	53
	3300	56	61	61	47	56	60	63	51
	3400	60	63	58	45	56	62	58	49
	3500	65	65	46	42	62	64	50	46
	3600	67	67	40	40	66	66	44	44
8/25	1400	69	69	38	38	70	70	38	38
	1500	73	69	34	38	75	70	35	38
	1600	74	69	33	37	75	71	34	37
	1700	74	70	32	37	75	72	33	36
	1800	73	70	32	36	77	74	33	34
	1900	71	70	35	36	75	74	33	34
	2000	69	68	37	39	68	71	38	38
	2100	66	65	33	43	62	67	37	42
	2200	63	63	36	47	60	64	39	46
	2300	60	60	42	50	58	61	44	50
	2400	58	58	47	53	55	58	52	53
	2500	57	57	51	55	55	56	55	56
	2600	56	55	54	57	54	54	57	59
	2700	55	54	56	59	53	52	58	60
	2800	54	53	60	60	51	51	62	62
	2900	53	53	60	60	51	51	62	62
	3000	52	53	61	60	50	51	63	62
	3100	52	55	62	58	50	53	65	60
	3200	53	58	61	55	50	55	65	56
	3300	62	61	49	50	54	59	54	52
	3400	65	65	43	45	61	63	46	46
	3500	71	70	38	39	67	68	39	40
	3600	75	75	34	34	72	72	34	34

SENSITIVITY ANALYSIS

Shade Subcomponent (Third Level)

Results of the sensitivity analysis of the shade subcomponent of fine fuel moisture are shown graphically in Figures 32 through 35 and in Appendix 1. Shade is a function of ten fourth-level factors (see Figure 2). In order of relative model sensitivity, these are: crown closure, crown length/diameter ratio, tree height, aspect, slope angle, latitude, time of day, month, tree type, and tolerance. Shade increases with crown closure, tree height, and crown length/diameter ratio, which act within the model to determine the stocking level of the stand. As the stocking level increases, so does shade. Latitude, aspect, slope angle, time of day, month, tree type, and tolerance modify the amount of shade at a particular stocking level. Latitude, time of day, and month (seasonal progression) increase shade. Aspect, slope, tree type, and tolerance work together to modify the effects produced by the other variables; the magnitude of their effects is also dependent on time of day, latitude and month.

Figure 32 shows the relationships between crown diameter, crown length, and shade. As crown diameter becomes a larger percentage of crown length, the ratio of crown length to diameter decreases, decreasing the stocking

FIGURE 32: SENSITIVITY ANALYSIS: SHADE BY CROWN LENGTH AND CROWN DIAMETER

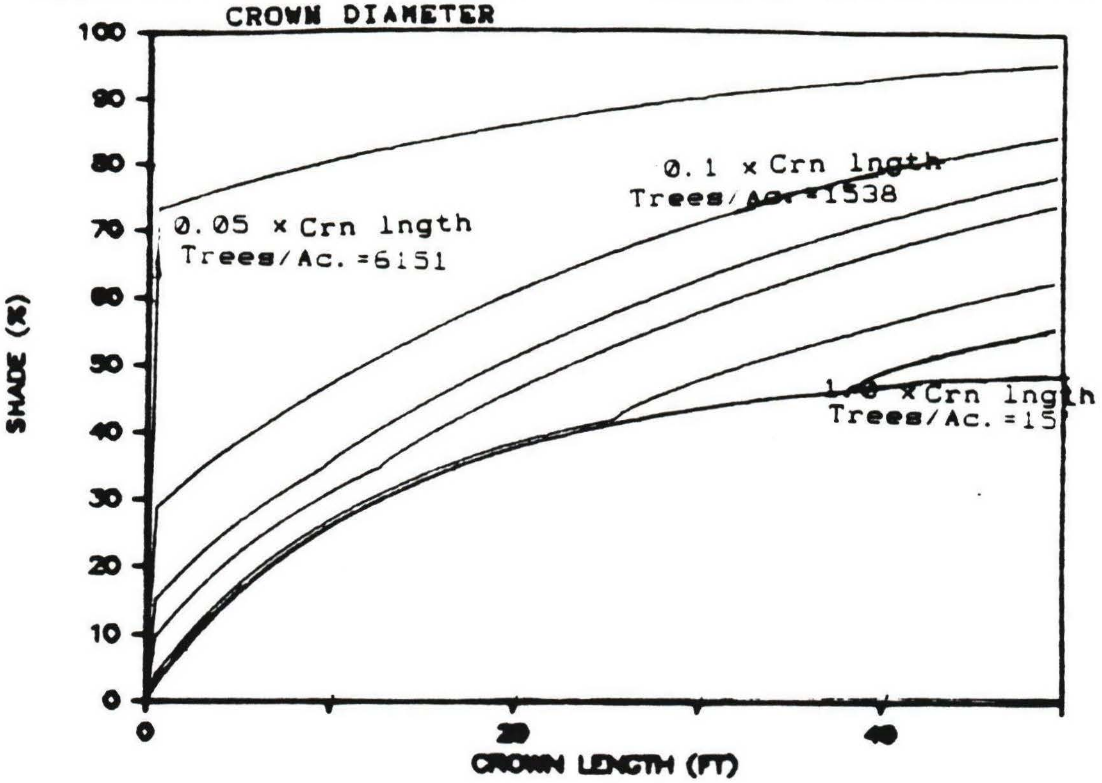
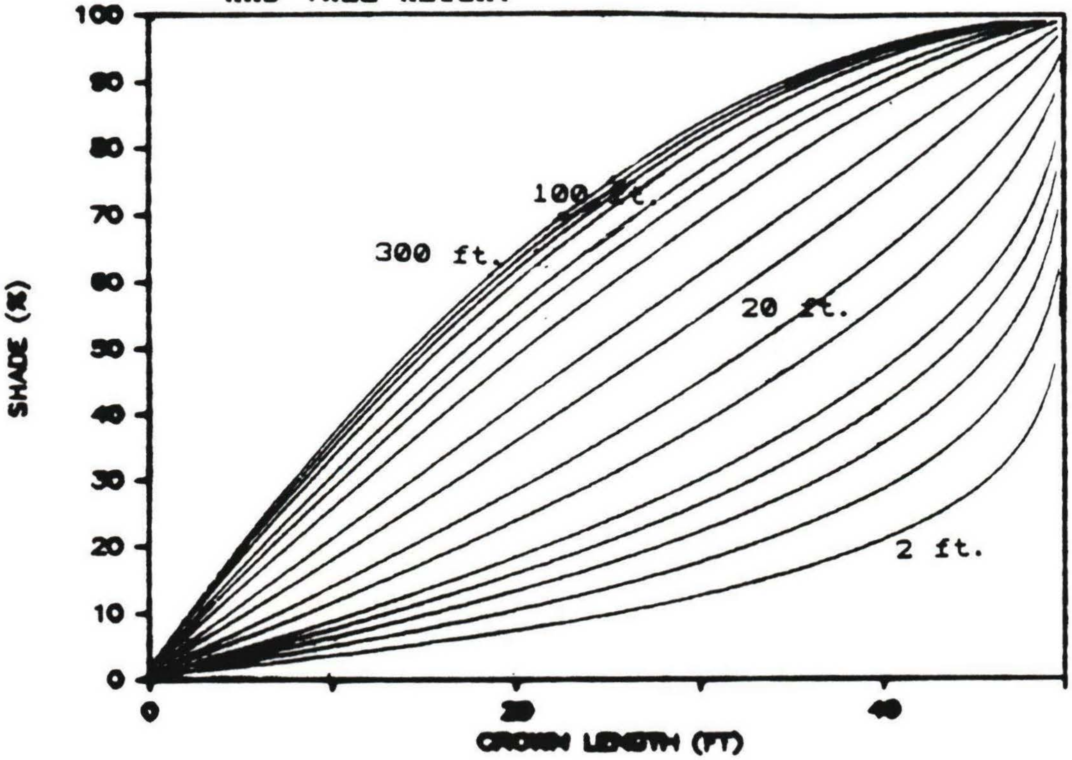


FIGURE 33: SENSITIVITY ANALYSIS: SHADE BY CROWN CLOSURE AND TREE HEIGHT



level of the stand, and decreasing shade. At a crown length of 30 feet, increasing the crown diameter from 5% to 100% of the crown length decreases the stocking level from 6151 to 15 trees per acre, and decreases the shade from 90% to 45%. Deciduous trees exhibit much the same response as conifers (Figure A, p. 90). Increasing the tree height from 50 to 100 feet serves to decrease the stocking level from 6151 to 1537 trees per acre, when crown diameter is 5% of crown length, and from 15 to 3.8 trees per acre when crown diameter is 100% of crown length (Figure B, p. 90 and Figure 32). The change in shade produced by this change in stocking level is not noteworthy, however. Latitude has a greater effect than does height on the influence of stocking level on shade. At 70 degrees north latitude, a difference in shade of about 20% is produced by changing the crown length from 25 to 50 feet, when crown diameter is 100% of crown length (Figure A, p. 91). At 45 degrees north latitude, the same shade difference is only about 5% (Figure 32). Latitude also affects the variability in shade produced by stocking level. At 45 degrees north latitude, there is a difference of 45% between the shade produced by high and low stocking levels (Figure 32). At 25 degrees north latitude, only 10% shade separates the two extremes (Figure B, p. 91).

Figure 33 shows the effect of crown closure and tree height on shade. When tree height is approximately 60

feet, a 1:1 relationship exists between crown closure and shade. At a crown closure of 50%, increasing tree height from 2 to 300 feet increases shade from 10% to 75%. Tree type does not affect this relationship. For deciduous trees (Figure A, p. 92), the same increase in tree height increases shade from 10% to 85%. Crown length/diameter ratio has a slightly greater effect on the relationship between shade and tree height at constant crown closure. For small crown length/diameter ratios (Figure B, p. 92), shade increases from 5 to 65% when tree height goes from 2 to 300 feet, at 50% crown closure. For large crown length/diameter ratios (Figure A, p. 93), the increase is from 25 to 90%. Tolerance does not greatly affect the relationship between tree height, crown closure, and shade (Figure B, p. 93; Figure A, p. 94; and Figure 33). Latitude has the greatest effect on the relationship between tree height, crown closure, and shade. At 25 degrees north latitude (Figure B, p. 94), 100-300-foot trees are required to achieve the 1:1 relationship between crown closure and shade present with 60-foot trees at 45 degrees north latitude (Figure 33). At 70 degrees north latitude (Figure A, p. 95), still shorter trees (20 feet) produce this relationship.

Figure 34 shows the effect of slope and aspect on shade at noon. On flat ground, shade is constant, regardless of aspect. The greater the slope, the greater

FIGURE 34: SENSITIVITY ANALYSIS: SHADE BY ASPECT AND SLOPE

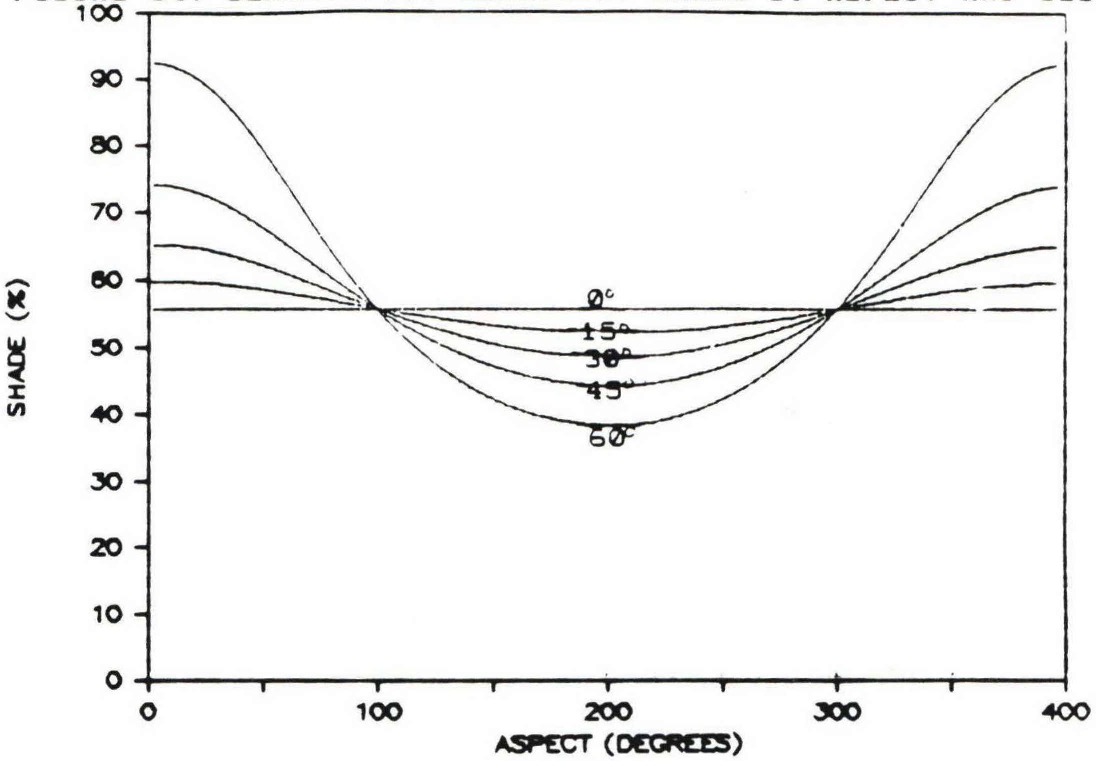
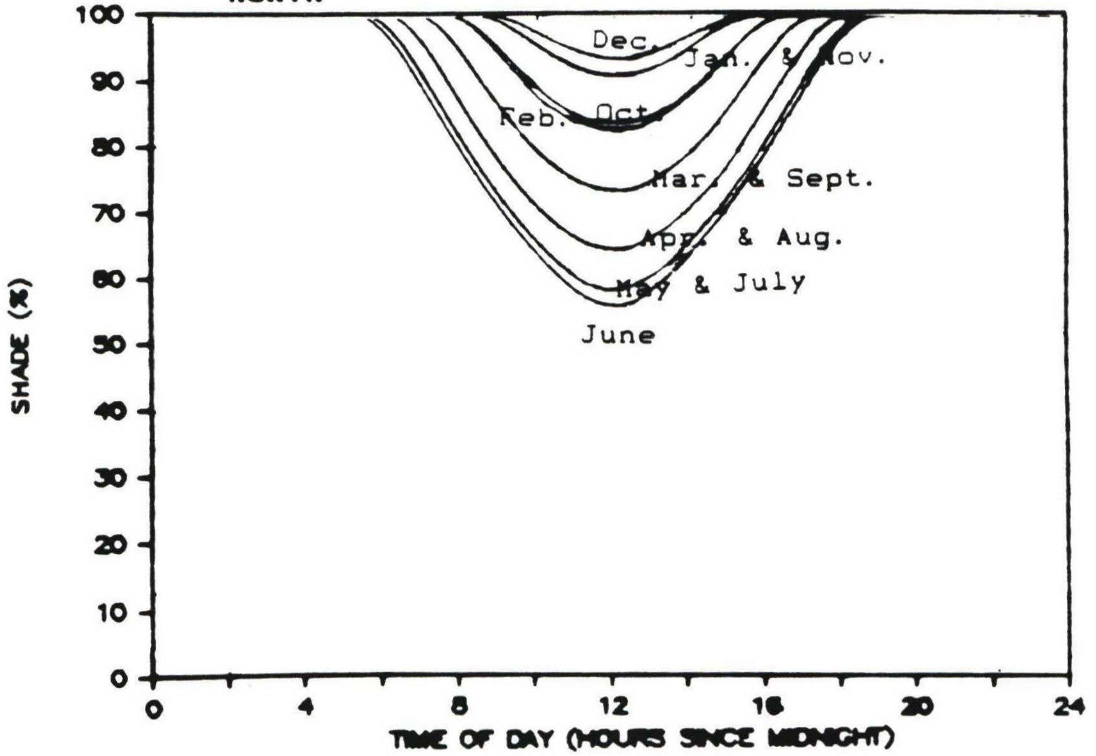


FIGURE 35: SENSITIVITY ANALYSIS: SHADE BY TIME OF DAY AND MONTH



the variance in shade between aspects. Changing the slope from 0 to 60 degrees reduces shade on the south aspect from 55 to 40%. On the north aspect, shade increases from 55 to 92%. Increasing latitude to 70 degrees enhances the effect of slope on shade (Figure B, p. 95). On the south aspect, increasing slope from 0 to 60 degrees reduces shade from 75% to 40%. On the north aspect, shade increases from 75% to 100% with a change in slope of 0 to 30 degrees. Time of day affects the relationship between slope, aspect, and shade by causing the compass point where shade is lowest to progress clockwise. By 6:00 pm (Figure B, p. 97), the point of lowest shade has moved from due south (180 degrees) to a west-southwest aspect (255 degrees). At midnight at 89 degrees north latitude (Figure B, p. 98), increasing the slope from 0 to 60 degrees decreases shade on the north aspect from 92 to 40%. The maximum change produced by slope occurs on the north aspect at this time and altitude. On east and west aspects, shade is 92% regardless of slope. On south aspects, shade is 100% regardless of slope. Changing the month from June to December produces the same effect at noon at 45 degrees north latitude that midnight in June at 89 degrees produces (Figure B, p. 99). Low crown closure dampens the effect of slope on shade, especially on south aspects. At 20% crown closure (Figure A, p. 100), increasing slope from 0

to 60 degrees lowers shade from 23 to 15%, on the south aspect. On the north aspect, shade is increased from 23 to 57%. The decreased crown closure lowers shade on flat ground from 55 to 23%. High crown closure increases the effect of slope on shade on the south aspect, but dampens it on the north aspect. At 75% crown closure (Figure B, p. 100), increasing slope from 0 to 60 degrees lowers shade from 80 to 60%, on the south aspect. On the north aspect, shade is increased from 80 to 100%. The increased crown closure raises shade on flat ground from 55 to 80%.

Figure 35 shows the effect of time of day and month on shade. Shade is greatest in magnitude and diurnal duration in December; least in June (Figure 35). There are twelve hours of complete shade in June, and eighteen in December, on south aspects when there is 50% canopy closure. The difference in magnitude of shade from June to December is about 40%. At 70 degrees north latitude (Figure A, p. 101), there is direct sun for longer periods of time (8 hours in December, 16 hours in June), although the amount of sun is less than at 45 degrees latitude (75% shade in June at 70 degrees latitude, compared to 55% at 45 degrees latitude). Low crown closure (20%) decreases the duration of shade for part of the year at high latitudes (Figure B, p. 101). In June, the ground is completely shaded only at midnight, but in December, there are still eighteen hours of complete shade under low crown closure. Low crown

closure also decreases the magnitude of shade. In June, there is 35% shade at low crown closure; 55% shade at 50% crown closure. At low latitudes with 50% canopy closure (Figure A, p. 102), there is greater magnitude of shade, especially in December, but the diurnal duration of shade in December is less than at mid latitudes (fourteen hours). The duration of shade in June remains the same. At low latitudes, tree height acts in the same manner as crown closure, but has less effect. The combination of tall trees and low crown closure decreases the total amount of shade slightly in June, but not in December, and does not affect the duration of shade (Figure B, p. 103).

Solar Intensity Subcomponent (Second Level)

Results of the sensitivity analysis of the solar intensity component of fine fuel moisture are presented in Figures 36 and 37 and in Appendix 2. Solar intensity is a function of four third-level factors (see Figure 2). In order of relative model sensitivity, these are: shade, "haze," solar elevation angle, and elevation above sea level. Solar intensity decreases with shade and haze, a term used to represent the effects of atmospheric turbidity. When no haze is present, there is a 1:1 relationship between shade and decreasing solar intensity,

regardless of elevation and solar elevation angle. With haze, the effect of shade on solar intensity is lessened. At a solar elevation angle of 15 degrees (Figure 36) with no shade, as haze is increased from 0 to 50%, solar intensity increases from 0.5 to 1.0 cal./sq. cm./min. High elevation increases solar intensity when haze and shade are non-zero; this effect is greatest at low values of shade and high values of haze. At 10,000 feet, when the solar elevation angle is 15 degrees, the solar intensity is about 0.18 when shade is 0 and haze is 50% (Figure A, p. 105).

Solar elevation angle also increases solar intensity when haze and shade are non-zero, more so than does elevation. Increasing the solar elevation angle from 15 to 30 degrees produces an increase in solar intensity from 0.5 to 0.25 cal./sq. cm./min., when shade is 0 and haze 50% (Figure B, p. 105). Increasing the solar elevation angle to 45 degrees causes solar intensity to increase to 0.35 cal./sq. cm./min., at zero shade and 50% haze (Figure A, p. 106). If elevation is also increased, to 5000 feet, the corresponding increase in solar intensity is to 0.45 cal./sq. cm./min. (Figure B, p. 106). At 10,000 feet, the solar intensity for zero shade and 50% haze is 0.55 cal./sq. cm./min. (Figure A, p. 107). At high solar elevation angles, no difference in solar intensity at low shade and 50% haze is produced by increasing solar

FIGURE 36: SENSITIVITY ANALYSIS: SOLAR INTENSITY BY SHADE AND HAZE (SOLAR ANGLE 15 DEGREES)

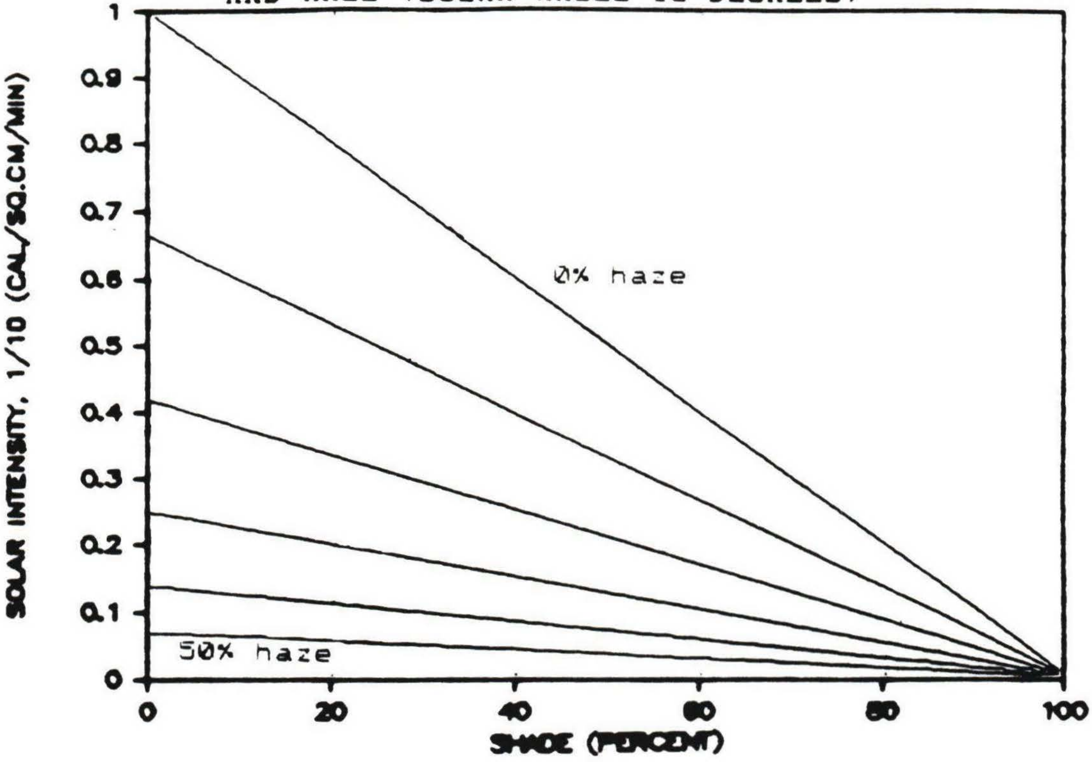
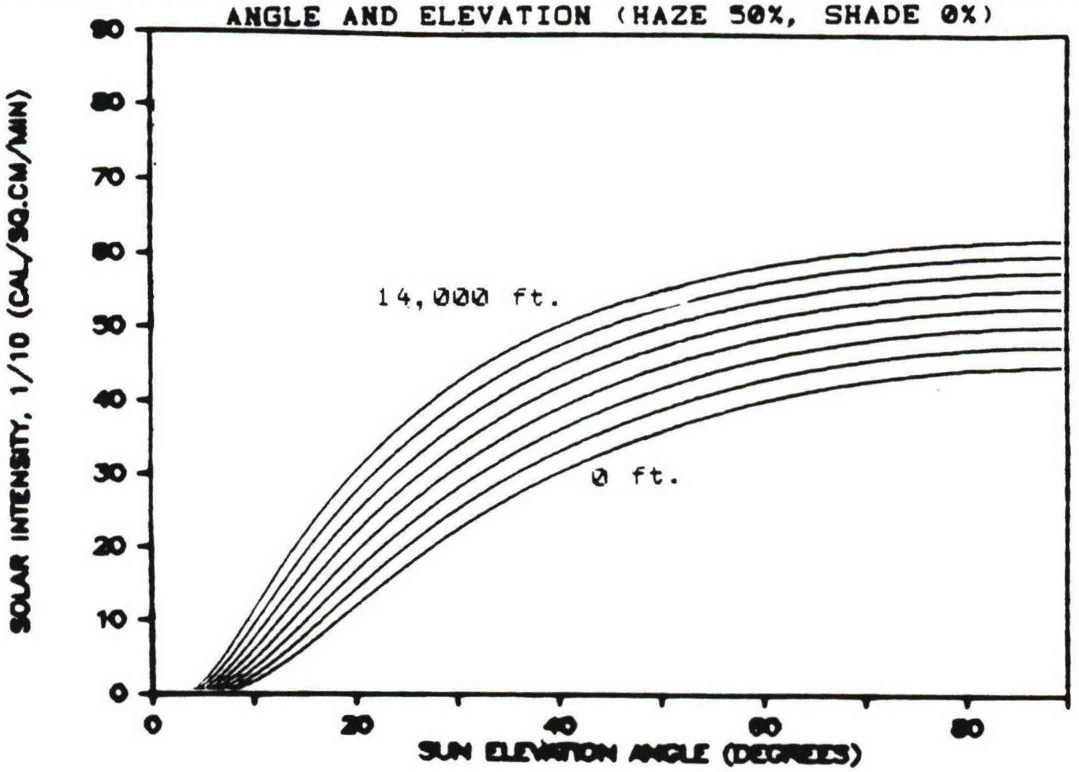


FIGURE 37: SENSITIVITY ANALYSIS: SOLAR INTENSITY BY SOLAR ANGLE AND ELEVATION (HAZE 50%, SHADE 0%)



elevation angle. When the solar elevation angle is increased from 75 to 90 degrees, the solar intensity at zero shade and 50% haze remains at 0.50 cal./sq. cm./min. (Figures A and B, p. 108). Elevation has the greatest effect on solar intensity at high solar elevation angle. Increasing the elevation from 0 to 10,000 feet when the solar elevation angle is 90 degrees increases the solar intensity to 0.65 cal./sq. cm./min. when shade is zero and haze is 50% (Figure A, p. 109).

The magnitude of increase in solar intensity with solar elevation angle depends on the levels of shade and haze. Figure 37 shows that at sea level, increasing the solar elevation angle from 0 to 90 degrees increases the solar intensity from 0 to 0.50 cal./sq. cm./min., when there is no shade and 50% haze. At 14,000 feet, solar intensity increases from 0 to 0.70 cal./sq. cm./min. At an "average forest haze" (25.5% haze), a solar elevation angle of 30 degrees is required to produce a solar intensity of about 0.50 cal./sq. cm./min. at sea level (Figure B, p. 109). With 50% haze, a solar elevation angle of 60 degrees is required to produce the same intensity (Figure 37). Low haze dampens the effect of solar elevation angle and elevation on solar intensity. At 5% haze, the maximum solar intensity is about 0.95 cal./sq. cm./min., regardless of elevation (Figure A, p. 110). High shade also dampens the effect of solar elevation angle and elevation on solar

intensity. When haze is 25.5% and shade is 50%, the maximum solar intensity is approximately 0.40 cal./sq. cm./min., regardless of elevation (Figure B, p. 109).

Fuel Temperature Rise Component (First Level)

Results of the sensitivity analysis of the fuel temperature component of fine fuel moisture are displayed in Figures 38 and 39 and in Appendix 3. Fuel temperature rise is a function of three second-level factors (see Figure 2). In order of relative model sensitivity, these are: solar intensity, windspeed, and fuel height. Solar intensity increases fuel temperature rise for all levels of windspeed and fuel height, although the rate of increase is modified by windspeed and fuel height.

When there is no wind, the fuel height does not affect the rise in fuel temperature with solar intensity. At zero windspeed, the maximum fuel temperature rise produced is 50 degrees F. at a solar intensity of 1.25 cal./sq. cm./min. (Figure 38; Figures A and B, p. 113; Figure A, P. 114). At moderate to high windspeeds, fuel height decreases fuel temperature rise. At windspeeds of 20 m.p.h., there is a maximum decrease of 20 degrees F. fuel temperature rise produced by an increase of three orders of magnitude in fuel height. For a fuel height of 0.01 feet, the maximum

fuel temperature rise is about 35 degrees F. (Figure 38). For 10-foot fuels, the maximum fuel temperature rise is 15 degrees F. (Figure A, p. 114).

As windspeed increases, fuel temperature rise decreases, for all levels of solar intensity and fuel height. The rate of decrease is faster with higher solar intensities and slower with taller fuels. When fuels are low (0.01 ft.), at a windspeed of 30 m.p.h., there is a 20 degrees F. increase in fuel temperature rise produced when the solar intensity is increased from 0.5 to 2.0 cal./sq. cm./min. (Figure 39 and Figure B, p. 115). When fuels are tall (100 ft.), the change in fuel temperature rise is only about 4.5 degrees F., under the same circumstances.

The greatest difference in fuel temperature rise between fuel heights occurs at high windspeeds. When solar intensity is low (0.5 cal./sq. cm./min.), the difference in fuel temperature rise between 0.01 foot fuels and 100 foot fuels is about 5.5 degrees F. (Figure 39). When solar intensity is high (2.0 cal./sq. cm./min.), the difference is about 21.5 degrees F. (Figure B, p. 115).

FIGURE 38: SENSITIVITY ANALYSIS: FUEL TEMP. RISE BY SOLAR INTENSITY AND WINDSPEED (FUEL HEIGHT 0.01 FT.)

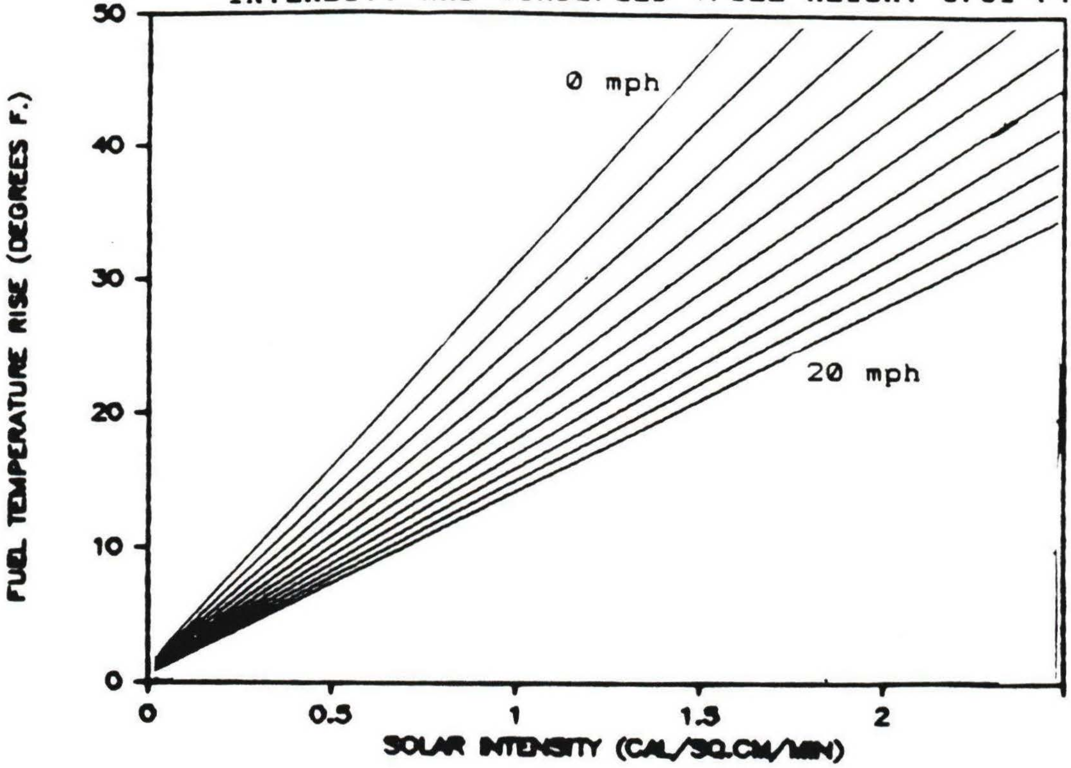
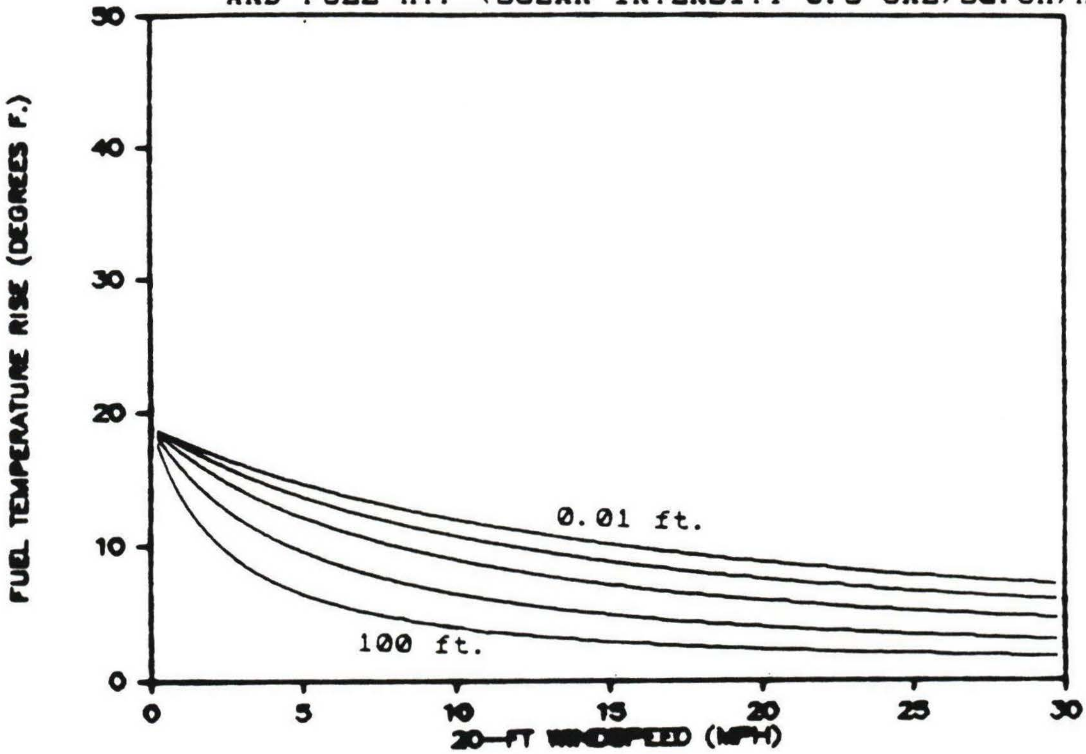


FIGURE 39: SENSITIVITY ANALYSIS: FUEL TEMP. RISE BY WIND AND FUEL HT. (SOLAR INTENSITY 0.5 CAL/SQ.CM/MIN)



Fine Fuel Moisture

Results of the sensitivity analysis of fine fuel moisture in the BEHAVE model are shown in Figures 40 and 41 and in Appendix 4. Fine fuel moisture is a function of five first-level factors: relative humidity, initial fuel moisture, fuel temperature, windspeed, and rainfall (see Figure 2). Interactions between these factors have more model sensitivity than do the factors themselves. In general, fuel relative humidity, initial fuel moisture, and rainfall increase fine fuel moisture; windspeed and fuel temperature have the opposite effect. Relationships among all variables are highly interdependent, however. Initial fuel moisture increases fine fuel moisture, depending on fuel relative humidity and temperature. At fuel temperatures below 100 degrees F., fine fuel moisture is higher for higher initial fuel moistures, regardless of fuel relative humidity. Fuel temperature does not substantially affect fine fuel moisture when relative humidity is high (Figure 40; Figures A and B, p. 117, Figure A, p. 118). A slight change is produced when initial fuel moisture is high and fuel relative humidity is low. An increase from 60 to 75 degrees F. in fuel temperature produces a decrease in fine fuel moisture of only about 3% (30% to 27%) when fuel relative humidity is zero and initial fuel moisture is 100% (Figure 40; Figure

FIGURE 40: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(FUEL TEMP. 60 DEGREES)

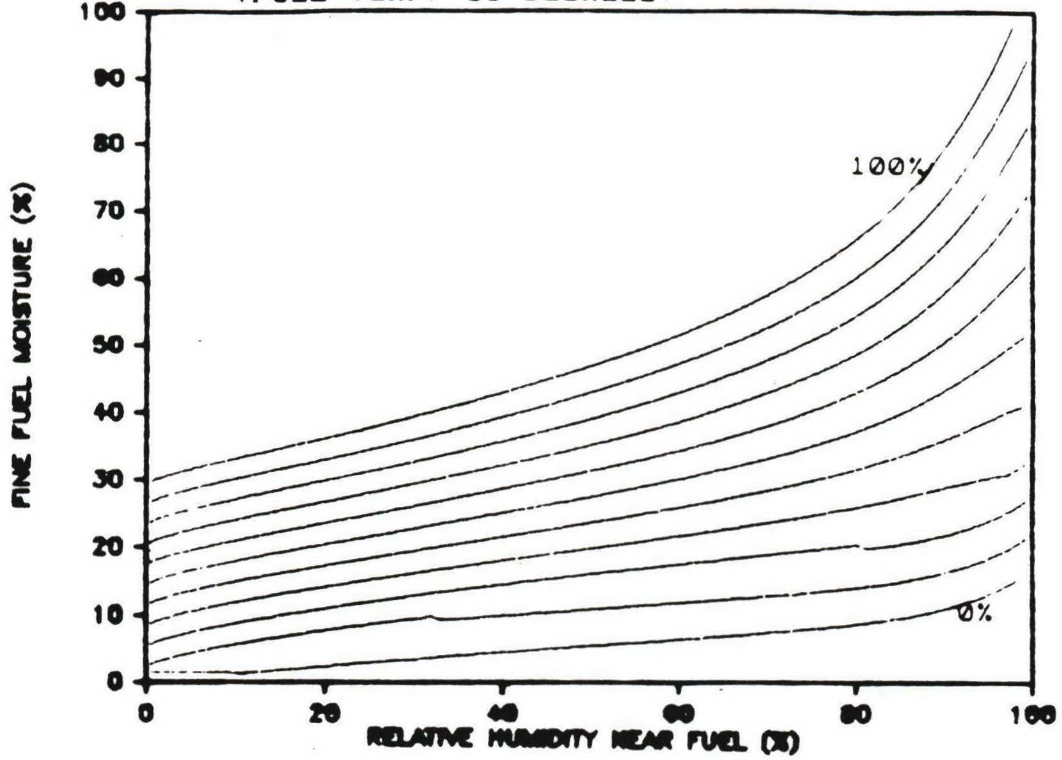
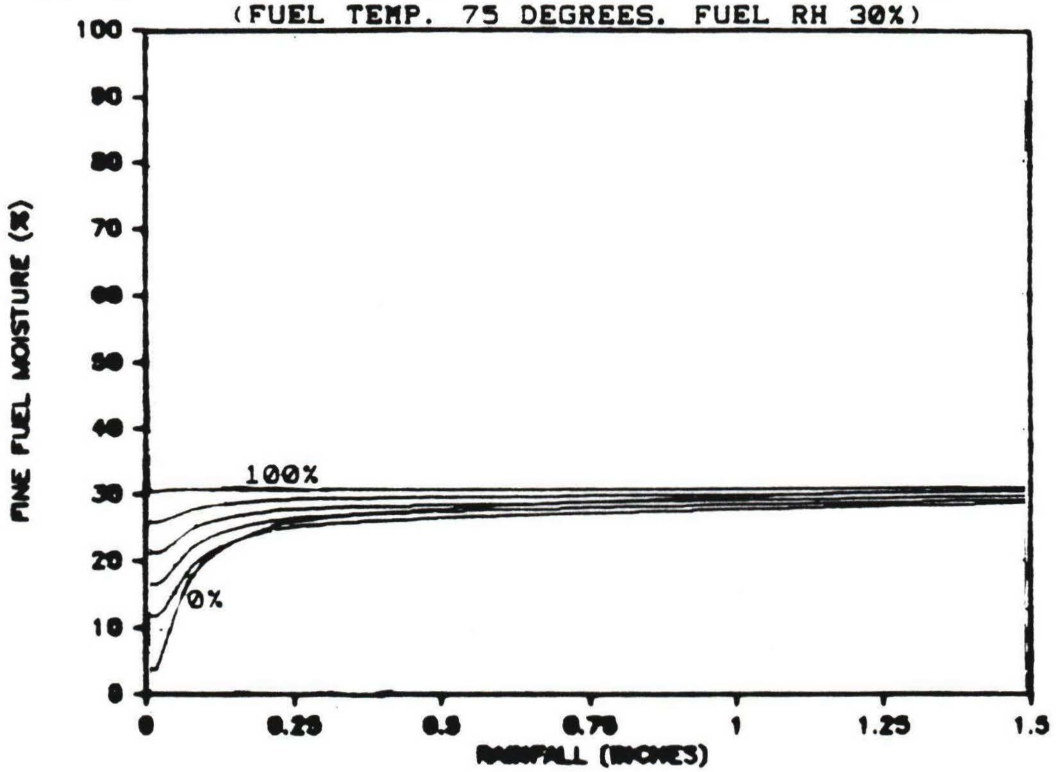


FIGURE 41: FFM BY RAINFALL AND INITIAL FUEL MOISTURE
(FUEL TEMP. 75 DEGREES. FUEL RH 30%)



B, p. 117). No change is noticeable when initial fuel moisture is low. Increasing the windspeed from 1 to 5 m.p.h. when fuel temperature is 75 degrees F. produces a decrease of about 6% fine fuel moisture (27% to 21%) when initial fuel moisture is 100% and fuel relative humidity is zero. The changes at high fuel relative humidity and low initial fuel moisture are not noticeable (Figures A and B, p. 117). At temperatures above 100 degrees, the relationship between initial fuel moisture and temperature depends on fuel relative humidity. When relative humidity is low, low initial fuel moistures produce high fine fuel moistures. When relative humidity is high, the opposite is true (Figure A, p. 125; Figures A and B, p. 119). As fuel temperature and windspeed increase, the value of relative humidity (at which the relationship between initial fuel moisture and fine fuel moisture reverses itself) increases. When fuel temperature is 100 degrees and windspeed is 5 m.p.h., it occurs at about 20% relative humidity (Figure A, p. 119). When fuel temperature is 120 degrees, with the same windspeed, it occurs at about 50% relative humidity (Figure B, p. 119). At windspeeds of 15 m.p.h., relative humidity must be over 70% before high values of initial fuel moisture generate high fine fuel moistures (Figure A, p. 120). When initial fuel moisture is zero, however, the relationship between fuel relative humidity and fine fuel moisture is the same regardless of fuel temperature or

windspeed.

Windspeed decreases fine fuel moisture at high levels of initial fuel moisture, but has little effect when initial fuel moisture is low. The same is true for fuel temperature. The magnitude of the decrease due to either temperature or windspeed depends on the initial fuel moisture and fuel relative humidity. Increasing the windspeed from 5 to 15 m.p.h. decreases the fine fuel moisture by about 15% when the fuel relative humidity is 60%, the fuel temperature 75 degrees, and the initial fuel moisture 100% (Figure B, p. 117; and Figure A, p. 118). When the initial fuel moisture is 50%, the decrease in fine fuel moisture at the same fuel relative humidity is about 8%, and when the initial fuel moisture is 20%, there is less than 1% difference.

Increasing the fuel temperature from 60 to 75 degrees F. decreases the fine fuel moisture by about 11% when the initial fuel moisture is 100%, 3% when the initial fuel moisture is 50%, and 2% when the initial fuel moisture is 20%, when the windspeed remains at 5 m.p.h. and the fuel relative humidity at 60% (Figure 40; Figure B, p. 117). The effect produced by the combination of fuel temperature and windspeed is not greatly different from that produced by windspeed alone, at least when the changes in fuel temperature and windspeed are relatively moderate. Increasing the fuel temperature from 60 to 75 degrees and

the windspeed from 5 to 15 m.p.h. decreases the fine fuel moisture by about 17% when the initial fuel moisture is 100%, 8% when the initial fuel moisture is 50%, and 1% when the initial fuel moisture is 20%, when the fuel relative humidity remains at 60% (Figure 40; Figure A, p. 118).

Rainfall increases fine fuel moisture when the initial fuel moisture is less than 100% (Figure 41; Figure B, p. 120; Figures A and B, p. 121; Figure A, p. 122). After a certain amount of rainfall, always less than 0.25 inch, no further increase in moisture occurs, regardless of the amount of rain. The point at which this occurs, as well as the magnitude and variability of fine fuel moisture, depends on initial fuel moisture, windspeed, fuel relative humidity, and fuel temperature. Increasing the fuel temperature from 60 to 75 degrees produces a decrease in fine fuel moisture of about 10% at an initial fuel moisture of 100%, a decrease of about 5% when initial fuel moisture is 60%, and no change when initial fuel moisture is 0%, at a fuel relative humidity of 75%, a windspeed of 1 m.p.h., and with no rainfall (Figures A and B, p. 121). Increasing the windspeed to 5 m.p.h. and decreasing the fuel relative humidity to 50% produces a decrease in fine fuel moisture of 23% at an initial fuel moisture of 100%, and a decrease of 15% at an initial fuel moisture of 60%, when fuel temperature remains at 75 degrees with no rainfall (Figure A, p. 121; Figure B, p. 120). Decreasing the fuel relative

humidity to 30% at the same windspeed, fuel temperature, and rainfall decreases the fine fuel moisture by about 8% at an initial fuel moisture of 100%, and about 3% at an initial fuel moisture of 60% (Figure 41; Figure B, p. 120). At 100-degree fuel temperatures, 15 m.p.h. windspeeds, and 50% fuel relative humidities, the high fuel temperatures and windspeeds so greatly reduce fine fuel moisture that the fine fuel moisture resulting from an initial fuel moisture of 0% is much higher than that resulting from other initial fuel moistures., except when there is no rainfall (Figure A, p. 122).

DISCUSSION

COMPARISONS OF ACTUAL VS. PREDICTED FINE FUEL MOISTURE

Daily Values

It is apparent from this study that BEHAVE is the most robust of the three fine fuel moisture models studied; it was consistently the best predictor across the range of aspect, canopy, and fuel conditions found in this experiment (Table 5, Figures 11-13). Simard and Main (1982) found, in a related study, that the FFMC worked better than the model used by the National Fire Danger

Rating System, a fore-runner of the FBO model, on moist sites. BEHAVE was not tested. In the present study, the FFMC surpassed the FBO model, but not BEHAVE, on the moist north aspect, closed-canopied site conditions. None of the models were very reliable for these site conditions, however. Needles on the very dry south aspect were best represented by the FBO model; again, this is consistent with the observations of Simard and Main (1982). The FFMC surpassed the other two models only for the intermediately-moist grass fuels, under the closed canopy on the south aspect, and under the open canopy on the north aspect. Both BEHAVE and the FBO model were able to predict fine fuel moisture more accurately than the FFMC when period length was short (one or two days following a rainfall). When period length was short, the FFMC commonly under-predicted on south sites and over-predicted on north sites. Only for periods as long as four to seven days did the FFMC achieve the accuracy of the other two models. Longer period lengths are more characteristic of wildfire management situations than are short period lengths since fire danger is greatest when weather is dry; the FFMC's unreliability for short period lengths may be less important for these situations. It could be more important in prescribed fire settings, where fire managers must wait for the proper weather and fuel moisture conditions to burn. It is possible that the right set of conditions

would occur shortly after a rainfall, in which case, the FFMC is not likely to yield useful predictions.

Time of year influenced the accuracy of all three models. The accuracy of both BEHAVE and the FFMC was greater during the late August/early September time period than any other. The FBO model remained consistent in its accuracy throughout August and early September. The models were all more accurate throughout August and in early September than they were during the cooler and moister late September/ early October time period. It is surprising that the FBO model was the best predictor late in the season, since it was developed for dry, worst-case fire conditions. The FFMC was developed for moist, shaded conditions, yet was less efficient late in the season than was the FBO model. The fact that BEHAVE also did not perform as well as the FBO model during this period is apparently at odds with the results of model comparisons by site condition, which showed BEHAVE as the best predictor on the wettest site conditions. However, it was necessary to eliminate most of the cases from the wettest site conditions late in the season, because the observed fine fuel moisture averaged over 30%. The late-season cases reflected mostly south aspects and open-canopied north slopes, which may explain the superiority of the FBO model for this time period. The fact that the sample size for this time period (n=28) was half the size of that for the

other two periods may also have affected the results.

Wildfires do not usually occur under conditions similar to those observed during late September and early October of 1984, thus the models' poor ability to predict during this period has implications only in terms of prescribed fire management. Since extreme differences (greater than 5% fuel moisture) between observed and predicted values during this period involved underpredictions only, any resultant management errors would be conservative errors, which might waste time and money, but would not have fire safety consequences.

Sources of variation in model predictions of early-afternoon fine fuel moisture include possible errors in all model inputs, as well as in timing of field sampling, and in fuel bed design. Many of the model inputs are coded variables; careful judgement was given to their selection, but errors are still possible. It is impossible to know the magnitude and extent of such errors, but since most coded variables are relatively minor in terms of model sensitivity, these errors, if present , should be of small consequence. Possible errors in measurement of weather variables, especially relative humidity, are more serious. BEHAVE is especially sensitive to relative humidity, yet this is one of the most difficult parameters to measure. It is not uncommon for relative humidity measurements to vary as much as 10% in one microsite, depending on its

method of measurement. This source of variation was controlled by using the hygrothermograph to measure relative humidity. This instrument is readily available to fire managers; thus, relative humidity inputs used in this study should reflect the accuracy of measurement obtainable by those who would use the model.

Field sampling should have been done during the hours of 2:00 to 4:00 p.m.; on certain days, this was not possible. Infrequently, samples were taken between 4:00 and 6:00 p.m. When the models were required to predict for days on which this occurred, diurnal, as well as daily fine fuel moisture values were calculated. Each model predicted an early-afternoon (2:00-4:00 p.m.) value, which was then adjusted for hourly changes to reflect the actual sampling time. The diurnal capabilities exhibited by BEHAVE and the FFMC in this test were poor, but it is doubtful that late sampling resulted in errors of great magnitude, since a maximum of 2 hours was involved. The FBO model, while not capable of round-the-clock hourly prediction, is able to adjust its predictions to allow for times slightly past 4:00 p.m.; thus, the magnitude of any error introduced by late sampling is probably low.

It is possible that the design of the fuel beds may have caused errors in measured values of fine fuel moisture. Fuel beds were used to localize fuels in specific areas which could be repeatedly sampled, and to

avoid live shrub ingrowth into the fuels; however, they were artificially arranged, rather than naturally-occurring. It was assumed that the moisture content of the fuels on the fuel beds accurately represents that of naturally-occurring fuels; it may be that this assumption is invalid. However, this does not seem likely, since the range of observed fuel moistures is reasonable for the site conditions and seasons represented.

Finally, many more cases with short period lengths could have been tested had this researcher's understanding of the BEHAVE inputs been complete before the study was begun. Sampling was always begun the day following a rain; in order to obtain the correct initial fuel moisture, sampling should have begun the day preceeding a rain. Without the correct initial fuel moisture, predictions for periods less than 3 days could not be performed, except when a rainfall occurred in the middle of a ten-day sampling session, in which case, the correct initial fuel moisture was available.

Diurnal Values

This study indicates that the fine fuel moisture model used in the BEHAVE system cannot, for the most part, accurately follow the diurnal wetting and drying of fine fuels, but that the Canadian FFMC is no more effective than the BEHAVE model, which requires less input. Two-tailed t-tests of model predictions showed that neither model was reliable for any site conditions. Analysis by the method of relative allowable error, however, showed that both models predicted reasonably well for the south aspect, closed-canopied sites (see Table 10). The model predictions were closer to observed values for these sites because the observed values of fine fuel moisture show less diurnal fluctuation under the canopy on the south site than they do in the open (see Figures 14-17 and 22-25), and the model predictions do not show great diurnal fluctuation. Moisture content under the canopy is about the same from 2:00-10:00 p.m. as that in the open, yet fuels wet up more slowly under the canopy as time passes, and moisture content under the trees falls below that in the open. From about midnight to 8:00 a.m., the canopy provides a barrier to nighttime re-radiation of longwave energy from the ground surface; less energy escapes into the atmosphere, and fuels cool less and take on moisture less rapidly. A similar phenomenon was observed by Simard (1968). It is

logical the models perform best on south aspect, closed-canopied sites, since mechanisms to account for the re-radiation of longwave energy are absent in their internal structure. Thus, the south aspect closed-canopied sites most closely represent conditions for which the models were built. Based on results of this study, researchers at the IFSL are working to develop a nighttime radiation algorithm for addition to the BEHAVE diurnal code; inclusion of a soil moisture/dewfall routine is also under consideration. It is expected that these changes will improve predictions dramatically.

The diurnal predictions given by the BEHAVE model are very close to those of the FFMC; this is because the diurnal logic within the two models is similar (Rothermel et al 1986). The major difference between the two is that the FFMC requires weather data input every hour between 2:00 p.m. and projection time; BEHAVE uses up to three transition-time (sunset, sunrise, and projection time) input values and estimates hourly values between these three. If one desired a fine fuel moisture prediction at 12:00 noon of the second day in a diurnal situation, he would need weather input for twenty-three hours to use the FFMC, but would need input for only four hours to use BEHAVE. This study shows that BEHAVE's weather estimates are very close to actual values, and that its accuracy of fuel moisture prediction is no worse than that of the FFMC.

In terms of fire management, the consequence of the inability of the BEHAVE system to model diurnal fine fuel moisture on most sites is that diurnal fire behavior predictions may be unreliable. Fire managers may need diurnal predictions in both prescribed and wildfire situations, at all times of the day and night. In prescribed fire situations, fires are set whenever managers can find the fuel moisture, temperature and relative humidity, and wind conditions to meet their prescriptions. Fires are often set during the evening, since humidities are higher than during the afternoon (there is less danger of extreme fire behavior), yet fuel moistures are still low enough for fires to burn. The hours between midnight and 6:00 a.m. are used less for setting fires, since humidities peak then (fuel moistures may be too high for fires to burn) and darkness presents a danger to workers. The hours between 6:00 and 10:00 a.m. are rarely used for starting prescribed fires; although humidities and fuel moistures are decreasing then, and it is light out, increasing safety conditions for workers, burns started then can rarely be completed before afternoon extreme fire danger begins. Afternoon fires are rarely set, except in the spring, since humidities and fuel moistures are lowest then, and the danger is greatest that flame height, intensity, and duff reduction may exceed the burning objectives.

In wildfire situations, managers may also need fire

behavior predictions throughout the day and night. Afternoon predictions are crucial, since it is during this time that fire behavior is most extreme. Evening and morning predictions may be necessary, not only to predict the extent of fires through changing rates of spread over time, but also to assess conditions for setting backfires or for burning out. Nighttime predictions may also be required, especially in cases where slopes are steep, winds are high, or fuels are volatile, causing fires to spread rapidly.

BEHAVE predictions are generally lower than actual fuel moistures, so that management decisions based solely on fire behavior predictions would err on the conservative side; it is possible that the greatest harm resulting from these errors would be in spending more money than is necessary to extinguish a fire. In prescribed fire situations, these errors may result in managers trying to set fires which, due to high fuel moistures, would never burn; again, a waste of time and money.

Errors in fine fuel moisture predictions may also have resulted from the fact that initial fuel moisture values for both diurnal cycles were estimated, rather than measured. Due to an incomplete understanding of this model input, moisture was not measured at 2:00 p.m. on the day before the diurnal cycle began, as it should have been. Instead, initial fuel moisture was taken as the 2:00 p.m.

value on the day the diurnal cycle began; i.e., it was assumed that moisture had not changed from one day to the next. While this is a legitimate way for fire managers to use the model, since no rain fell between the two days (Rothermel, pers. comm. Oct., 1985), it does introduce an uncontrolled source of variation, and does not comply with the original intent of the experiment to preserve the integrity of all model inputs. Sources of variation in field measurement of fine fuel moisture include the timing of sampling and fuel bed design. The BEHAVE model was run as though all 40 samples for each hour (5 fuel beds x 8 site conditions) had been taken at exactly the same time in the field; this was, in actuality, not done. Approximately one hour was required to sample all four sites; therefore, sampling began and ended on the half hour. For example, if an 8:00 sampling was to be done, sampling was begun at 7:30 and continued through 8:30. This was true for all sampling times except the three hours around sunset (8:00, 9:00, and 10:00 p.m.) and the three hours around sunrise (6:00, 7:00, and 8:00 a.m.); at these times, two researchers were available to take samples, and sampling time was reduced to half an hour. It was assumed that half an hour either side of a sampling time would not substantially affect the BEHAVE output. Any effect would most likely show up as a time lag between the field measurements and the BEHAVE predictions; no lag was seen. At the level of accuracy

exhibited by the BEHAVE model, this error was deemed minor.

SENSITIVITY ANALYSIS

Shade Subcomponent (Third Level)

It is not possible, in this type of sensitivity analysis, to give quantitative values to the importance of any factor in determining fine fuel moisture; one can only rank the factors according to relative importance. With so many variables to determine shade, interactions between factors can be more important than single factors alone. This means that, although certain factors have a greater influence on shade than others, more minor variables may combine to substantially alter the effect of primary variables.

Crown closure, taken by itself, has the largest effect on shade. Crown length/diameter ratio and tree height may interact with crown closure to increase or lessen the shade produced by a certain level of crown closure, depending on the levels of all factors. Low levels of crown length/diameter ratio decrease shade. Tree height increases shade, when crown closure is low, but is of little consequence under high crown closure. Taller trees may compensate for low crown length/diameter ratios. Crown

diameter, if narrow, can be fairly important in determining shade. Stands with narrow crowns are assumed to be dense by the model, and are assigned high values of shade. In these cases, crown length is less important in determining shade. Crown length is most important when the stand is more open; longer crowns can compensate for lower stocking density in such situations.

Latitude may affect the influence of crown length on shade; at high and low latitudes, crown length has a greater influence than in the mid-latitudes. Stocking level itself is of less importance at low latitudes, because of the lower amount of shade produced there in general, and of greater importance at high latitudes, where there is greater variability of shade. Tolerance class does not greatly affect the amount of shade produced by crown closure, except in stands of deciduous trees with wide crowns, at low latitudes.

Aspect has less of a direct effect than crown closure on shade, although under certain combinations of slope angle, crown closure, season, time of day, and latitude, it becomes more important. Aspect has no effect on shade if the ground is flat. Steep slopes cause more variation in shade with aspect, although time of day and season may cause even gentle slopes to exhibit great variation in shade with aspect. The variability due to time of day is greater than that due to season. There is more variability

in shade with aspect at high latitudes, as long as slopes are steep, than at mid-latitudes, although latitude does not cause shade to vary as much with aspect as season or time of day does. Crown closure does not greatly affect the influence of aspect on shade, except when crown closure is low and slopes steep.

Time of day has a large direct effect on shade; this effect depends somewhat on season, latitude, crown closure, and tree height. Shade is least at noon. The effect of time of day on shade is greatest during the month of June; this is especially true at low latitudes. Low crown closures at high latitudes also increase the effect of time of day on shade, as do tall trees at low latitudes.

Solar Intensity Subcomponent (Second Level)

Results of the sensitivity analysis of the solar intensity component of fine fuel moisture show that shade and haze have the greatest effect on solar intensity within the model; elevation has the least effect. Only when there is high haze is the influence of elevation noticeable. Solar elevation angle determines intensity in the absence of shade and haze. In the absence of haze only, shade controls solar intensity, and solar angle has a minor effect. Together, high sun angle and elevation have a

greater effect than they do separately; they greatly reduce the importance of haze in determining solar intensity, although they do not detract from the importance of shade.

Fuel Temperature Rise Component (First Level)

Of the variables which determine fuel temperature in the BEHAVE fine fuel moisture model, solar intensity has the greatest effect, although its effect may be modified by windspeed and fuel height. Fuel height alone has no effect on fuel temperature; it is only in combination with windspeed that fuel height affects temperature rise. Windspeed affects temperature rise the most when solar intensity is high and fuels tall, although its effect is still substantial when fuels are low. When solar intensity is low, windspeed has a very small effect on fuel temperature rise.

Fine Fuel Moisture

Results of the sensitivity analysis on fine fuel moisture show that combinations of rainfall, fuel relative humidity, initial fuel moisture, and fuel temperature have a much greater effect on fine fuel moisture than do any of

these factors separately. Fuel relative humidity has a greater influence on fine fuel moisture when the initial fuel moisture is high; rainfall has less effect on fine fuel moisture. When fuel temperature is high, both fuel relative humidity and initial fuel moisture have less effect on fine fuel moisture. Windspeed also reduces the effect of fuel relative humidity and initial fuel moisture. Fuel temperature alone has a greater influence than does windspeed alone. The combination of the two factors has no more effect on fine fuel moisture than they do separately.

Inductive reasoning suggests that the factors which have the largest effect on shade would also be very important in determining fine fuel moisture itself, since shade is one of the most important factors determining solar intensity, and solar intensity has the most control over fuel temperature, an important component of fine fuel moisture. It is not possible to show this directly in a sensivity analysis of this nature, however, because of the complex interactions which occur between factors. The effects of fourth-level subcomponents on fine fuel moisture may be damped out by combinations of other factors as BEHAVE proceeds to calculate fine fuel moisture.

Originally, one intent of this sensivity analysis was to identify factors which had little effect on fine fuel moisture, so that researchers responsible for improving the BEHAVE model could consider their removal from the lengthy

list of model inputs. However, the results have shown that there always seems to be at least one situation in which even the most minor of variables emerges as important, due to the combination of other factors. For this reason, and because it is the intent of the NFFL to have the model as applicable as possible to any situation it may encounter, results of this study do not suggest the removal of any factor from the model. A complete sensitivity analysis might be able to discover such factors, however.

SUMMARY

To summarize:

1. Although statistical analysis showed the BEHAVE, FFMC, and FBO models all to be poor predictors of early-afternoon fine fuel moisture, a non-statistical analysis of relative allowable error between predicted and observed values showed that BEHAVE was the best predictor, followed by the FBO model, and then the FFMC.
2. The FBO model was the best predictor of early-afternoon fine fuel moisture for the driest conditions found in this study. On intermediately-moist sites, BEHAVE was superior for needle fuels; the FFMC for grasses. On the very

wettest treatments, no model predicted well, although BEHAVE achieved the greatest accuracy.

3. BEHAVE was the best predictor of early-afternoon fine fuel moisture when rain had fallen within two days. When three to seven days had passed since a rainfall, the FBO model was the best predictor. All three models estimated to within 20% RAE more than half the time when at least four days had passed without rain.
4. The FBO and BEHAVE models were more accurate in predicting early-afternoon fine fuel moisture throughout August and early September than was the FFMC; no model was able to predict to within 20% RAE more than 40% of the time in late September and early October.
5. Neither BEHAVE nor the FFMC could accurately follow the diurnal wetting and drying of fine fuels on any except the south aspect, closed-canopied treatment. Differences between predictions made by the two models are slight, owing to the similarity in their diurnal codes.
6. Crown closure has the greatest effect on the shade component of fine fuel moisture in the BEHAVE model. Crown length/diameter ratio and tree height modify the effect of crown closure. Latitude, aspect, slope, time of day, and season cause

tremendous variation in shade with crown shape and density variables.

7. The solar intensity component of fine fuel moisture in the BEHAVE model is most sensitive to the variables shade and haze, which can be modified noticeably by solar angle, but not ordinarily by elevation.
8. Solar intensity is the main determinant of the fuel temperature component of fine fuel moisture in the BEHAVE model. Windspeed and fuel height modify its effects.
9. Combinations of factors have more direct effect on fine fuel moisture than do single factors. Because of the importance of the interaction of minor factors, it is not recommended that any model inputs be dropped due to low model sensitivity.

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*APPENDIX 1

SENSIVITY ANALYSIS OF SHADE SUBCOMPONENT

OF FINE FUEL MOISTURE

*Baseline values (Table 3) apply, except where otherwise noted.

FIGURE A: SHADE BY CROWN LENGTH AND CROWN DIAMETER FOR DECIDUOUS TREES

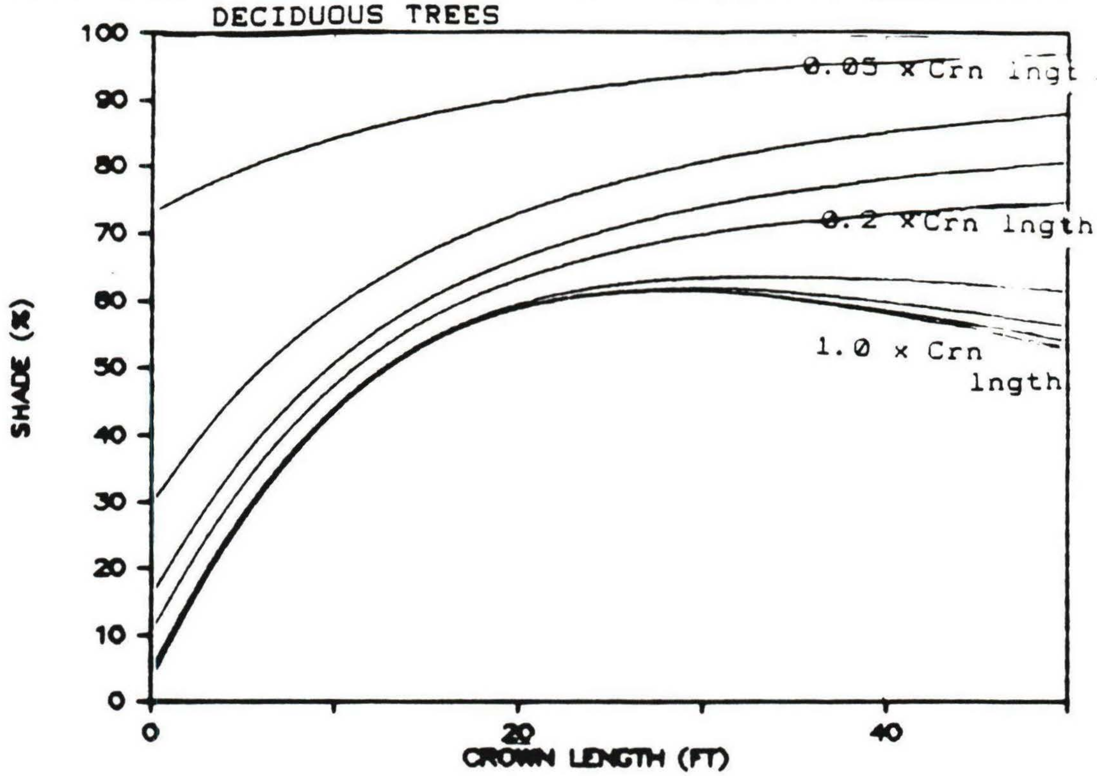


FIGURE B: SHADE BY CROWN LENGTH AND CROWN DIAMETER FOR TALL TREES AT 45 N. LATITUDE

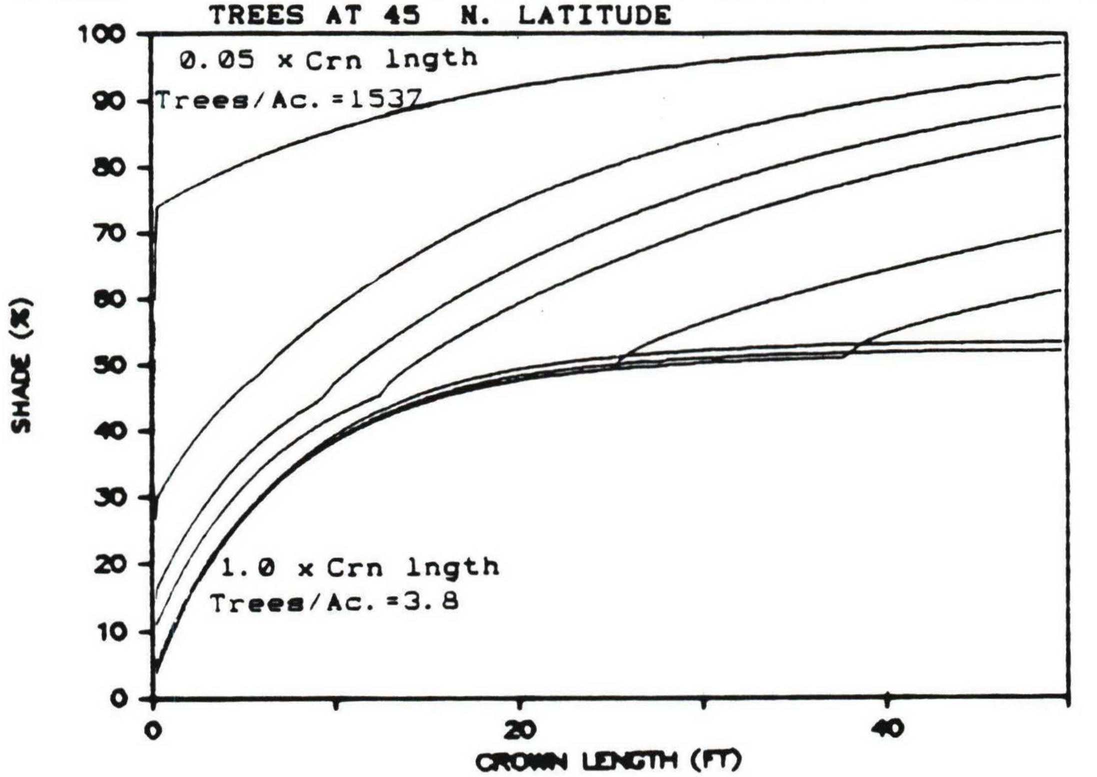


FIGURE A: SHADE BY CROWN LENGTH AND CROWN DIAMETER T 70 N. LATITUDE

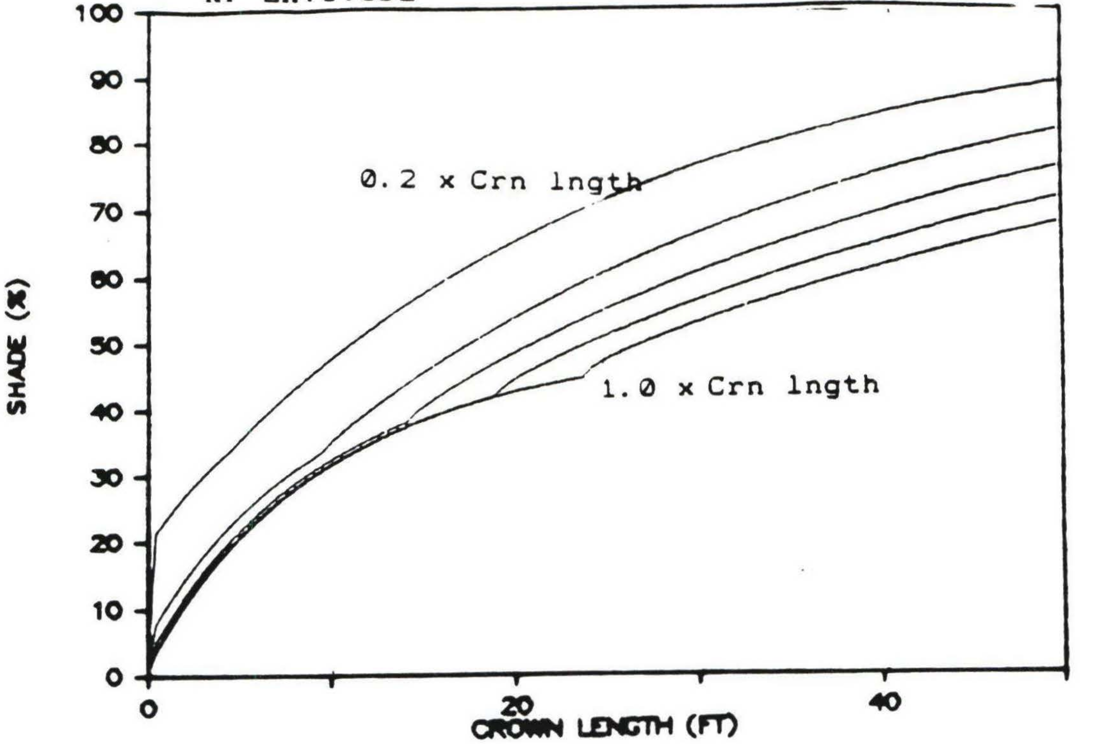


FIGURE B: SHADE BY CROWN LENGTH AND CROWN DIAMETER AT 25 N. LATITUDE

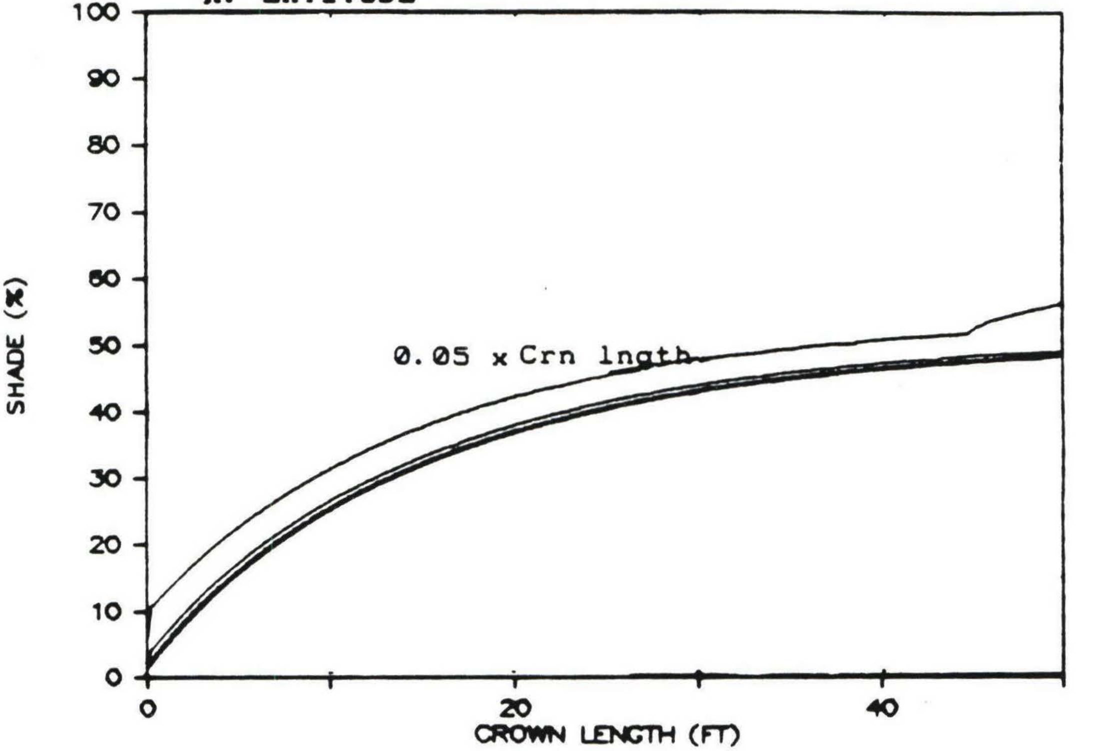


FIGURE A: SHADE BY CROWN CLOSURE AND TREE HEIGHT FOR DECIDUOUS TREES

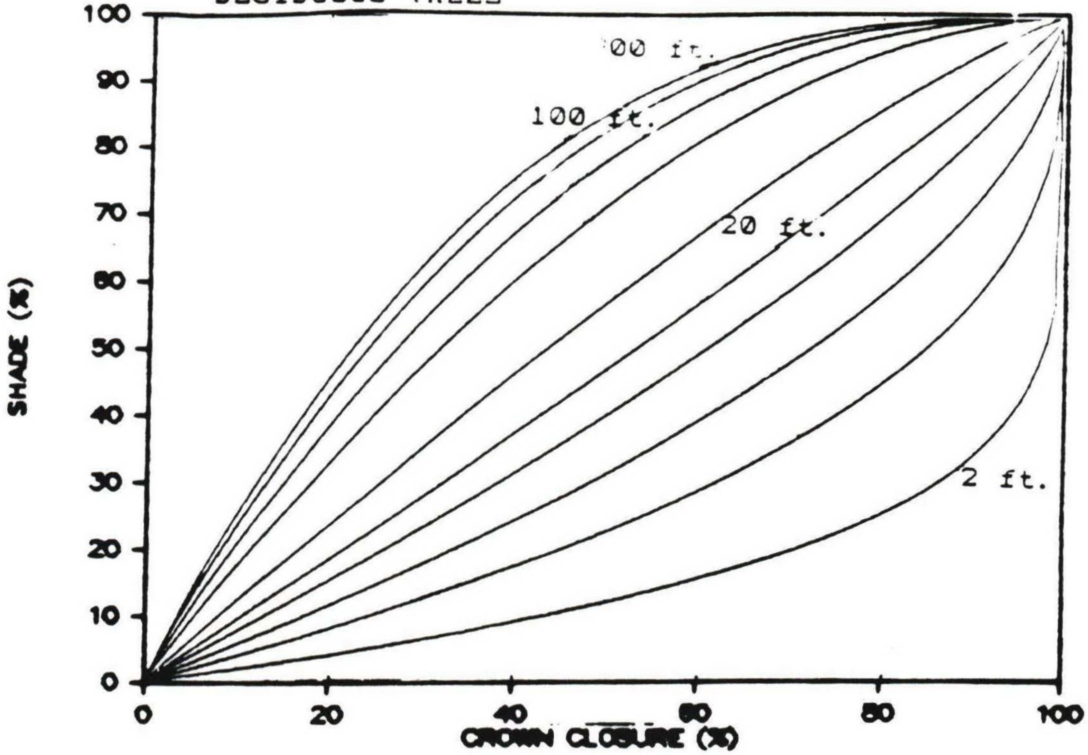


FIGURE B: SHADE BY CROWN CLOSURE AND TREE HEIGHT FOR SHORT, WIDE CROWNS

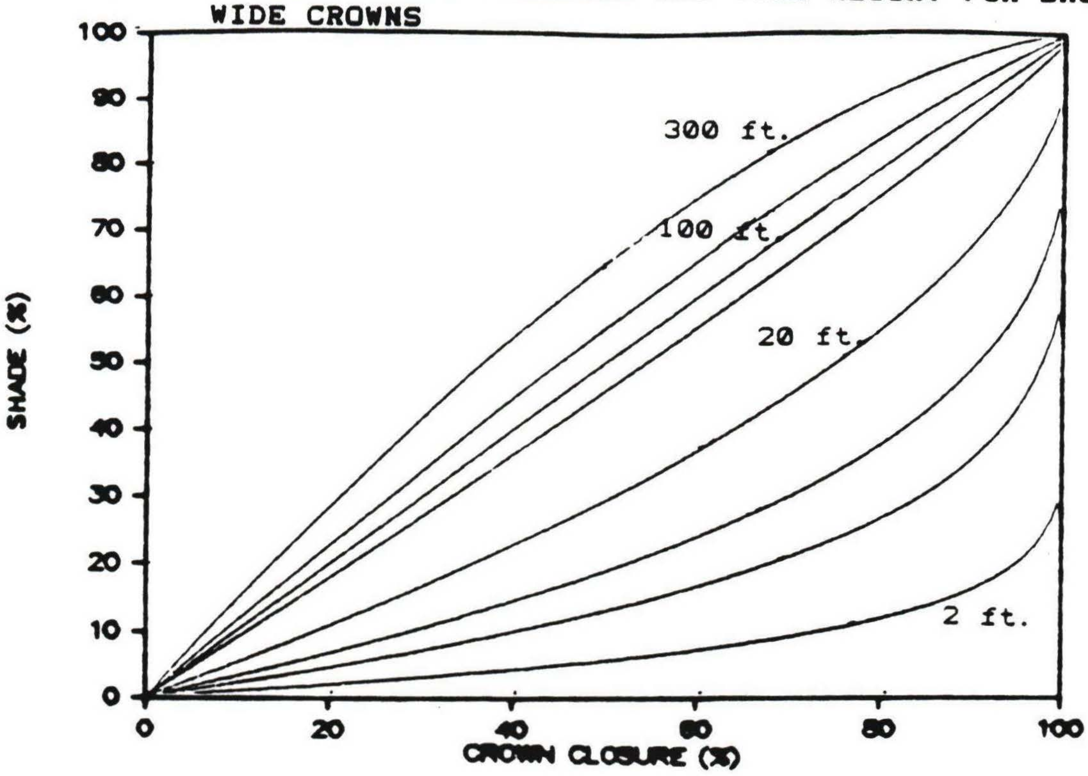


FIGURE A: SHADE BY CROWN CLOSURE AND TREE HEIGHT FOR TALL, NARROW CROWNS

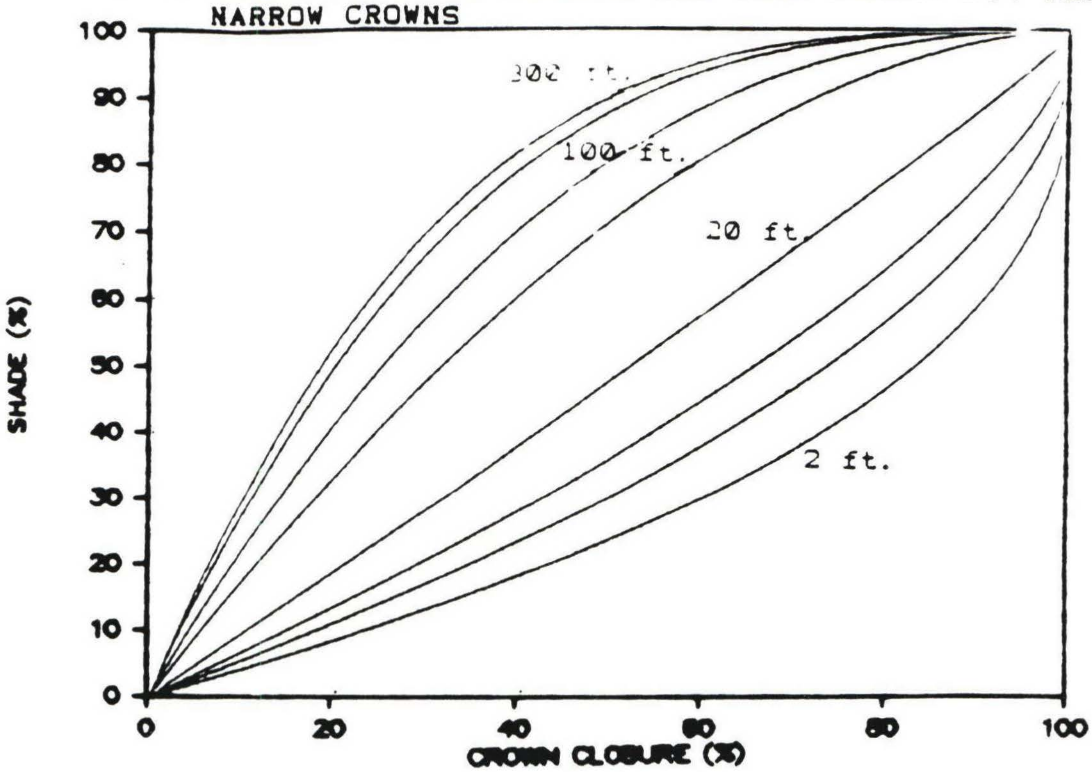


FIGURE B: SHADE BY CROWN CLOSURE AND TREE HEIGHT FOR INTOLERANT SPECIES

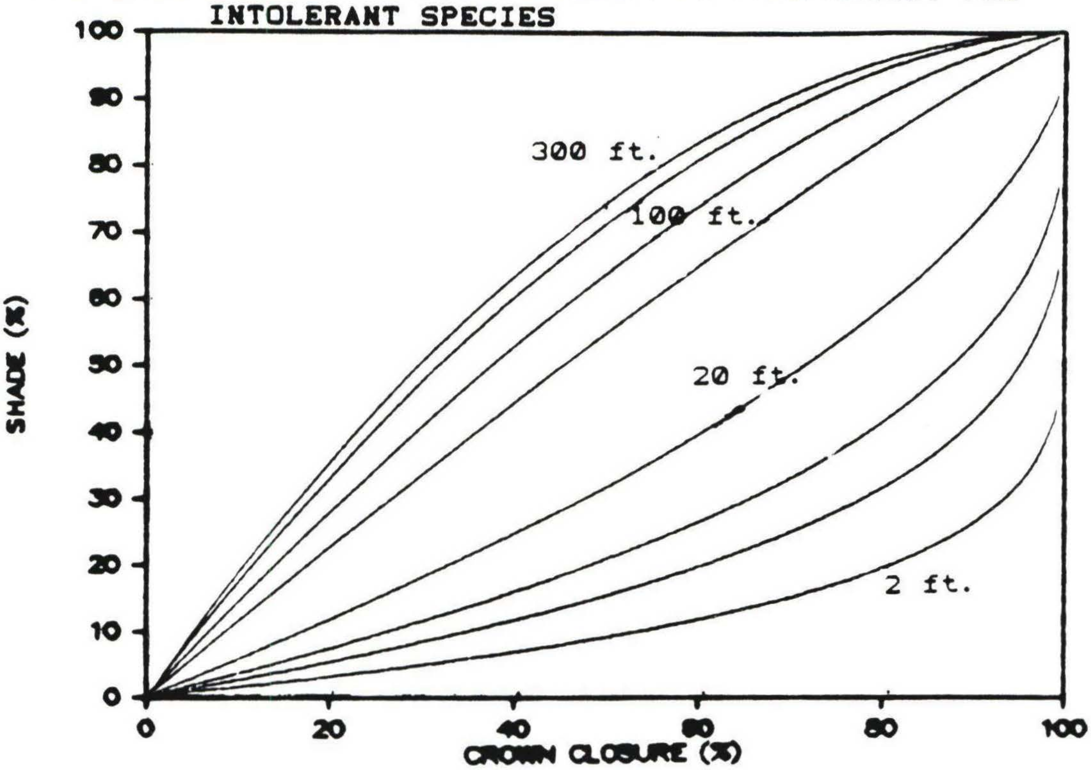


FIGURE A: SHADE BY CROWN CLOSURE AND TREE HEIGHT FOR VERY TOLERANT SPECIES

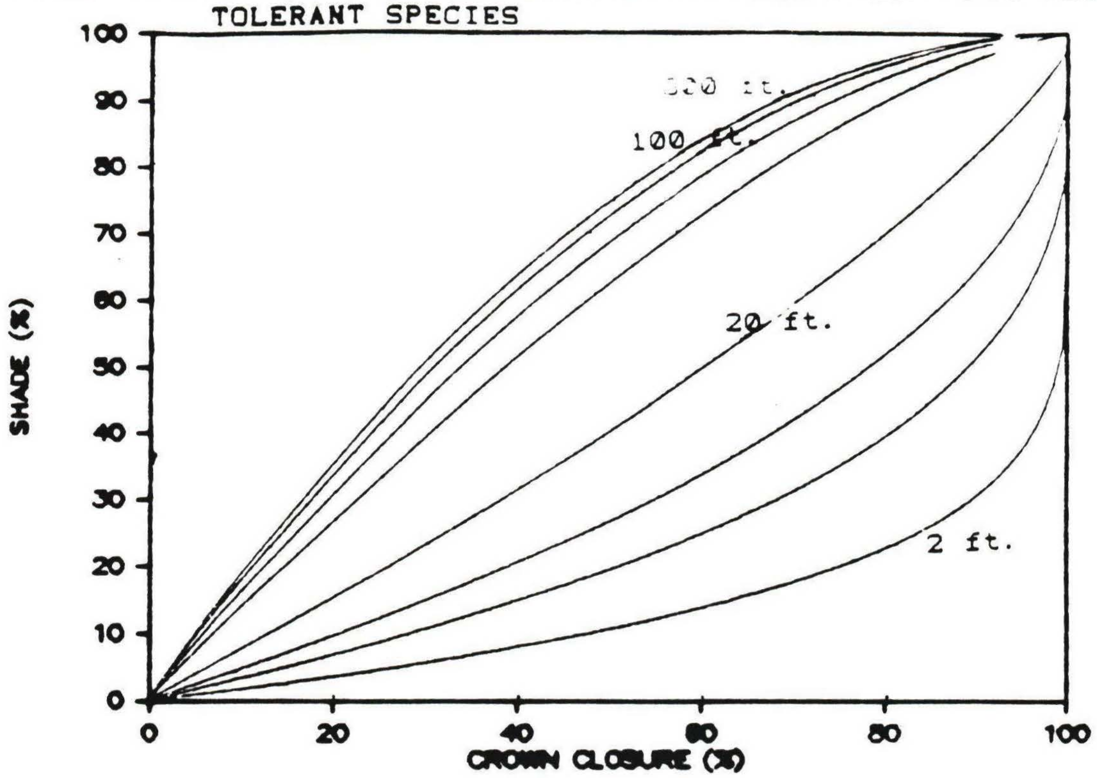


FIGURE B: SHADE BY CROWN CLOSURE AND TREE HEIGHT AT 25 N. LATITUDE

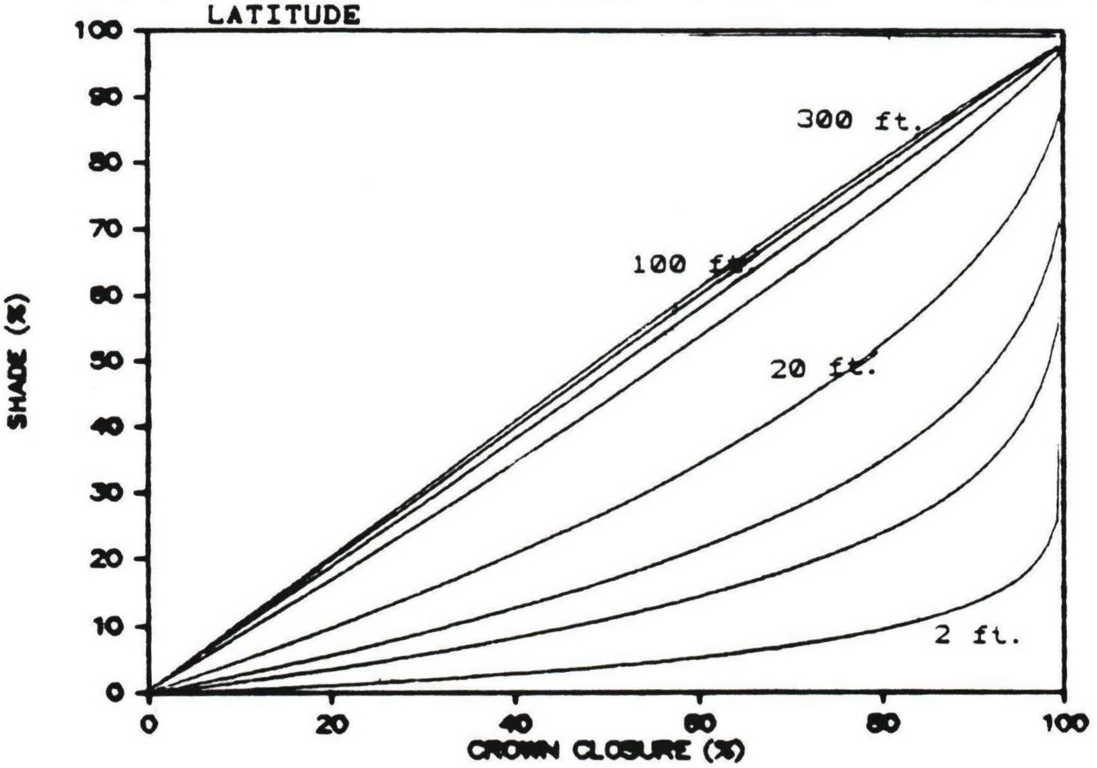


FIGURE A: SHADE BY CROWN CLOSURE AND TREE HEIGHT AT 70 N. LATITUDE

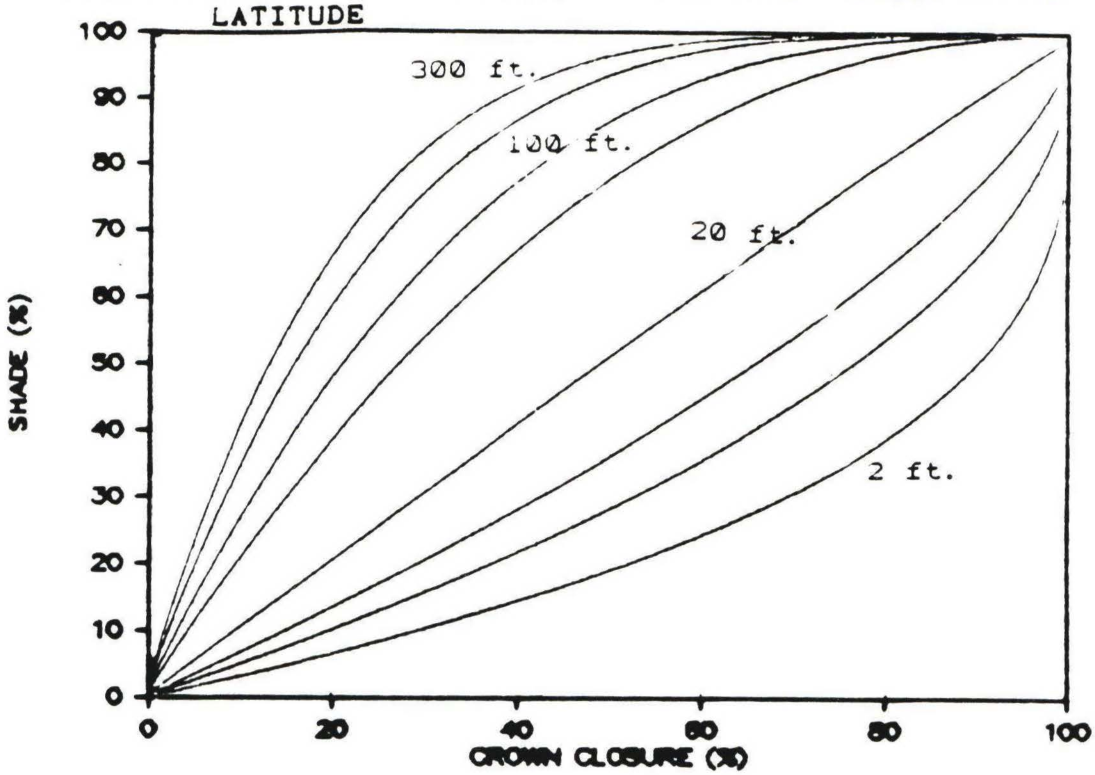


FIGURE B: SHADE BY ASPECT AND SLOPE AT 70 N. LATITUDE

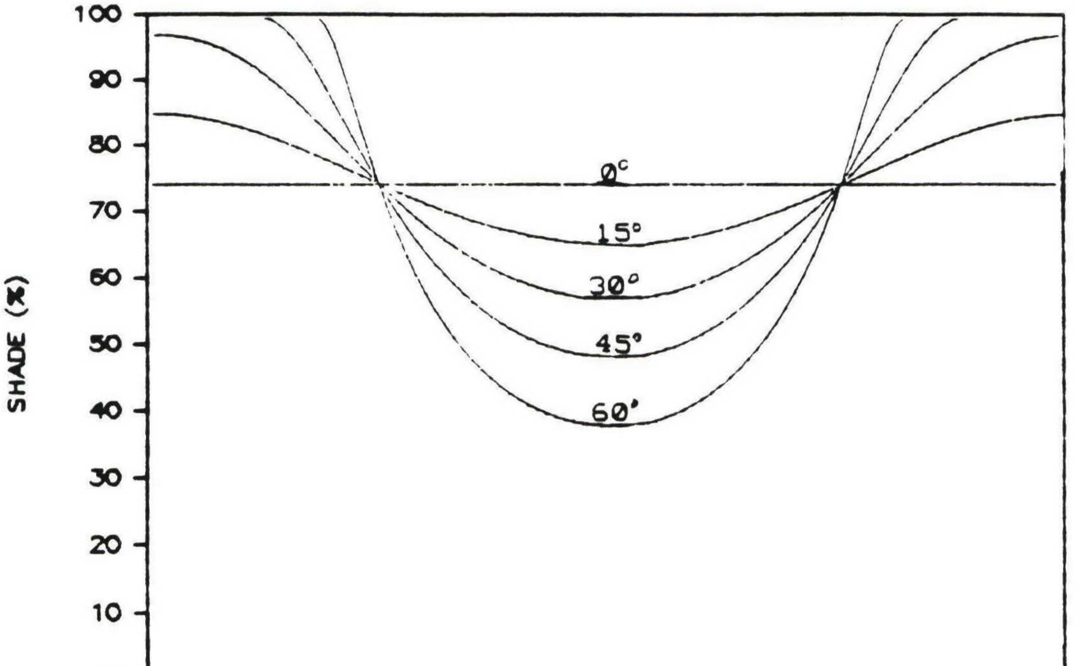


FIGURE A: SHADE BY ASPECT AND SLOPE AT 3:00 PM

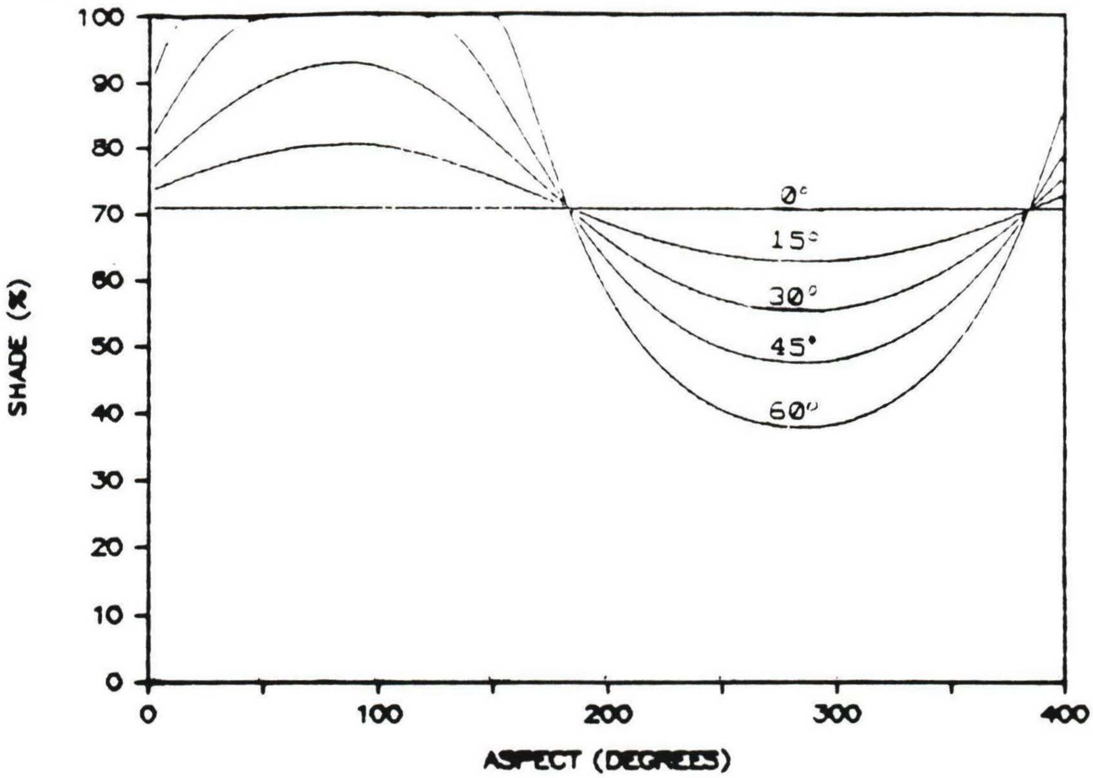


FIGURE B: SHADE BY ASPECT AND SLOPE AT 4:00 PM

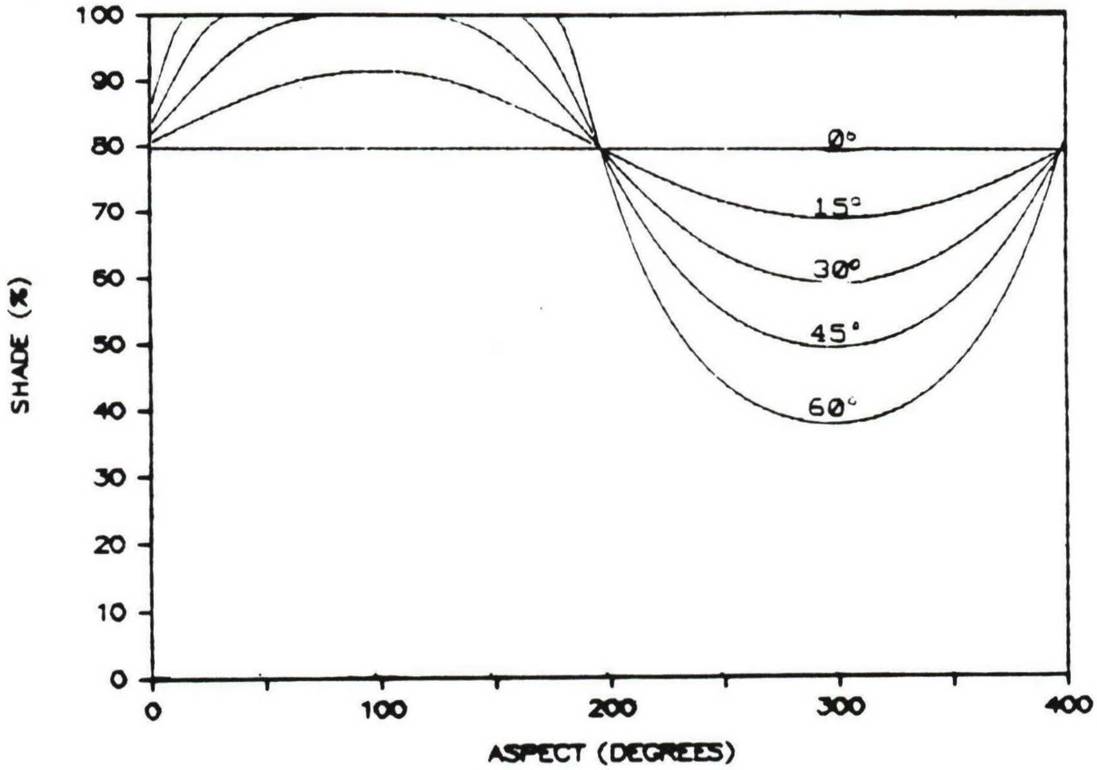


FIGURE A: SHADE BY ASPECT AND SLOPE AT 5:00 PM

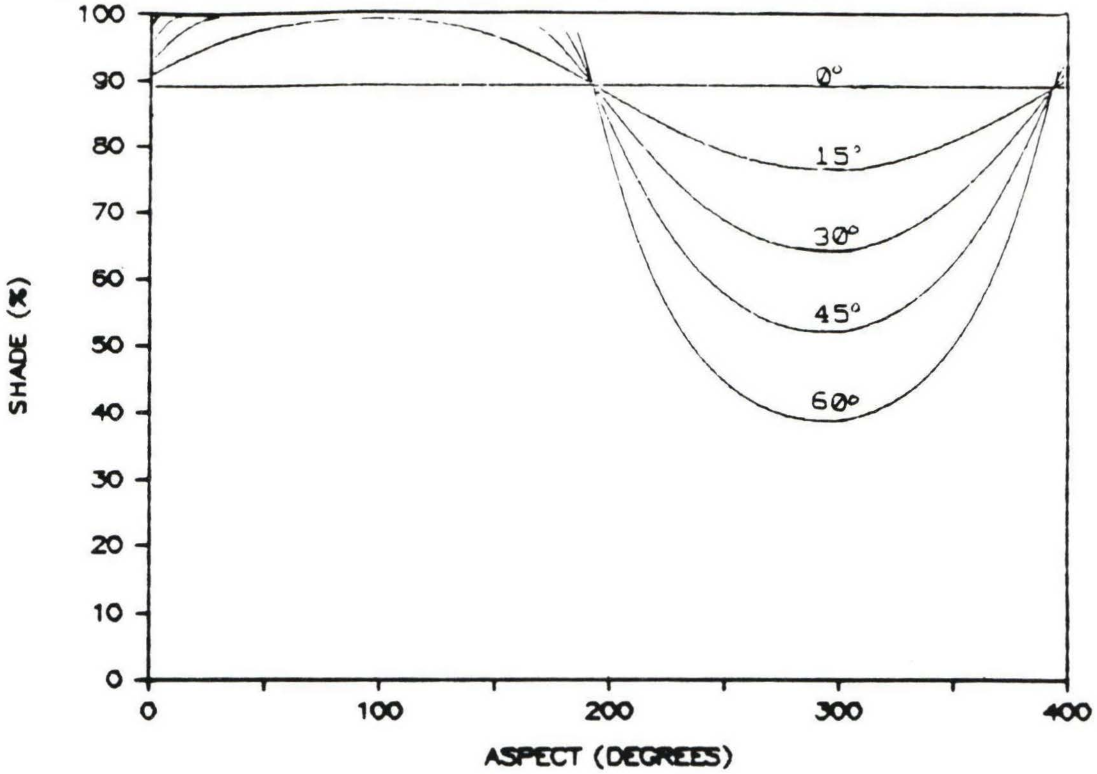


FIGURE B: SHADE BY ASPECT BY SLOPE AT 6:00 PM

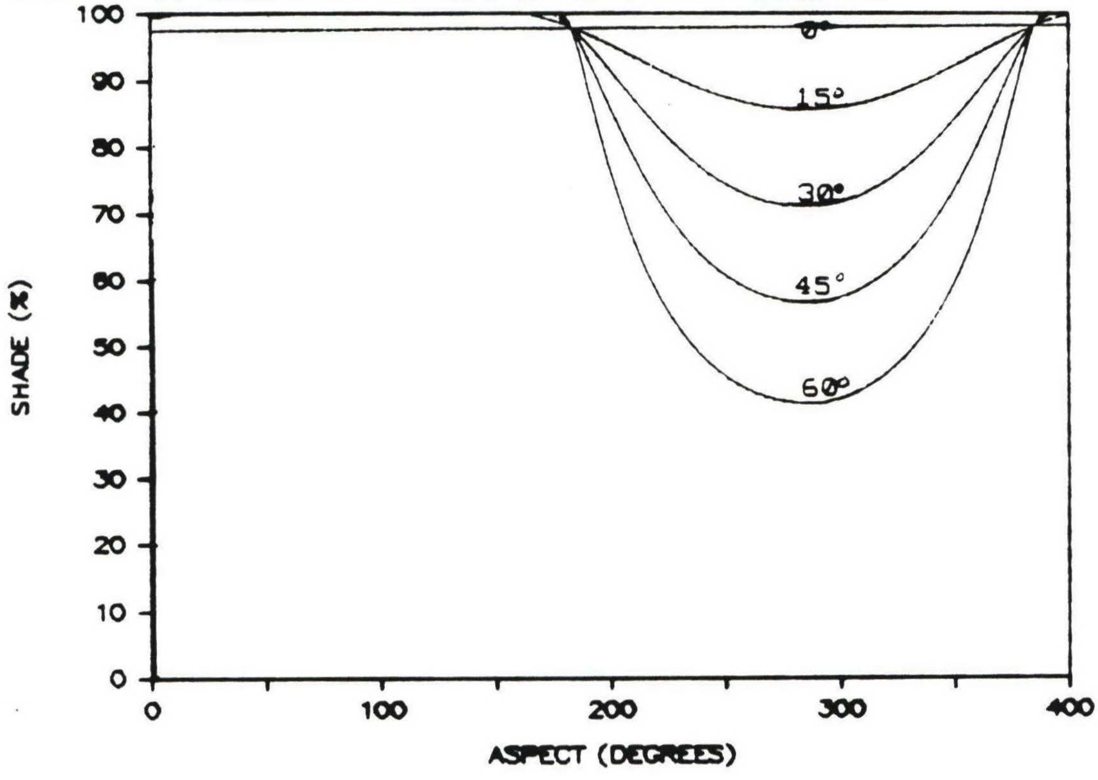


FIGURE A: SHADE BY ASPECT AND SLOPE AT 75 N. LATITUDE AT 9:00 PM

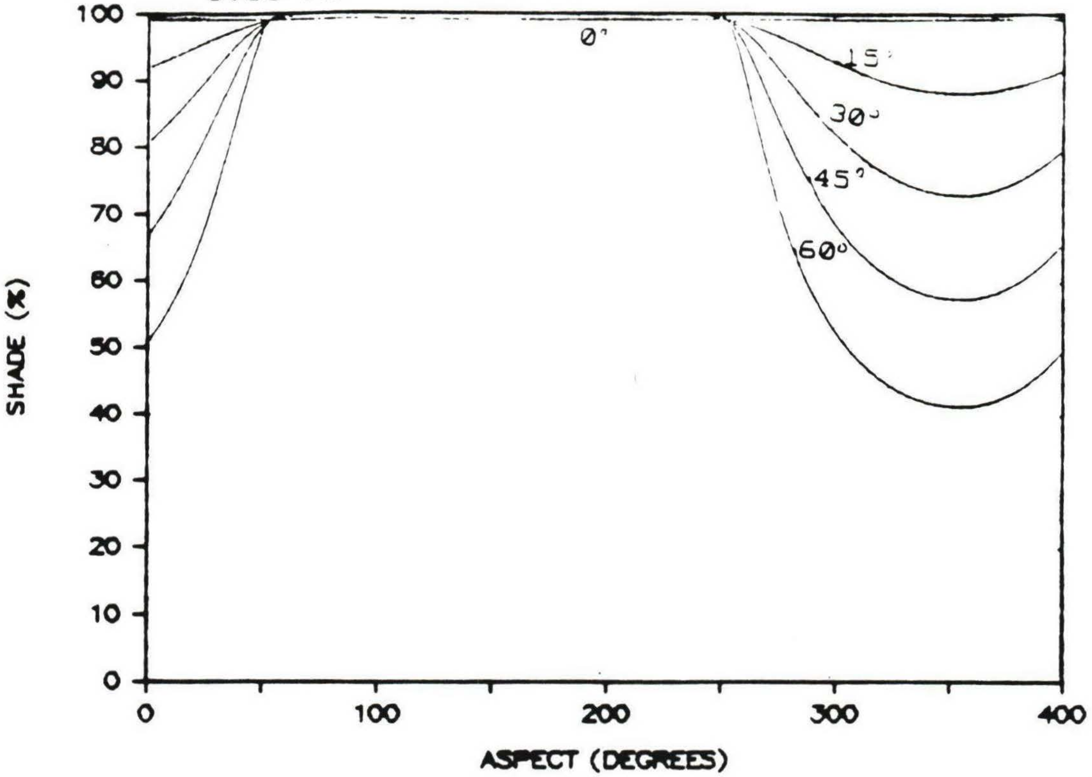


FIGURE B: SHADE BY ASPECT AND SLOPE AT 89 N. LATITUDE AT 12:00 AM

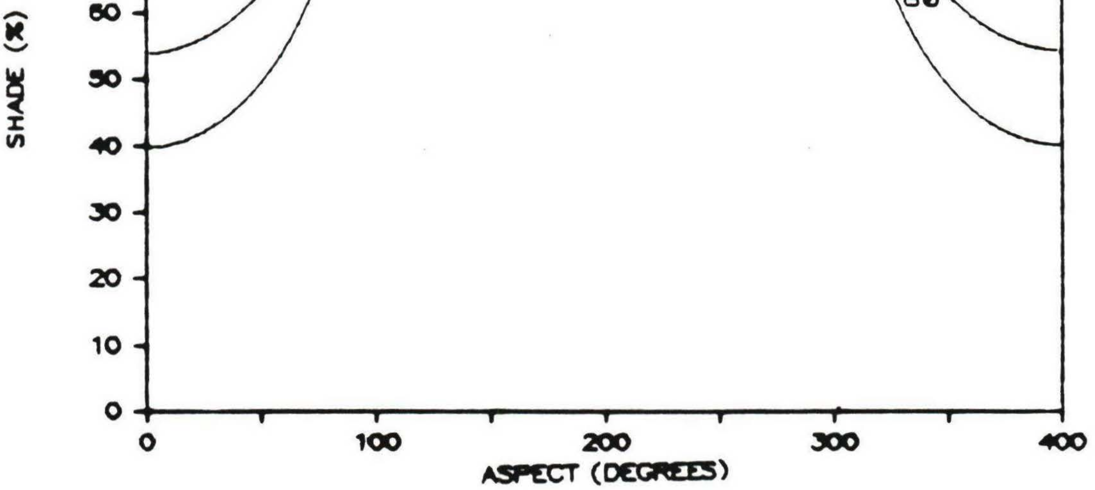


FIGURE A: SHADE BY ASPECT BY SLOPE ON SEPT. 21

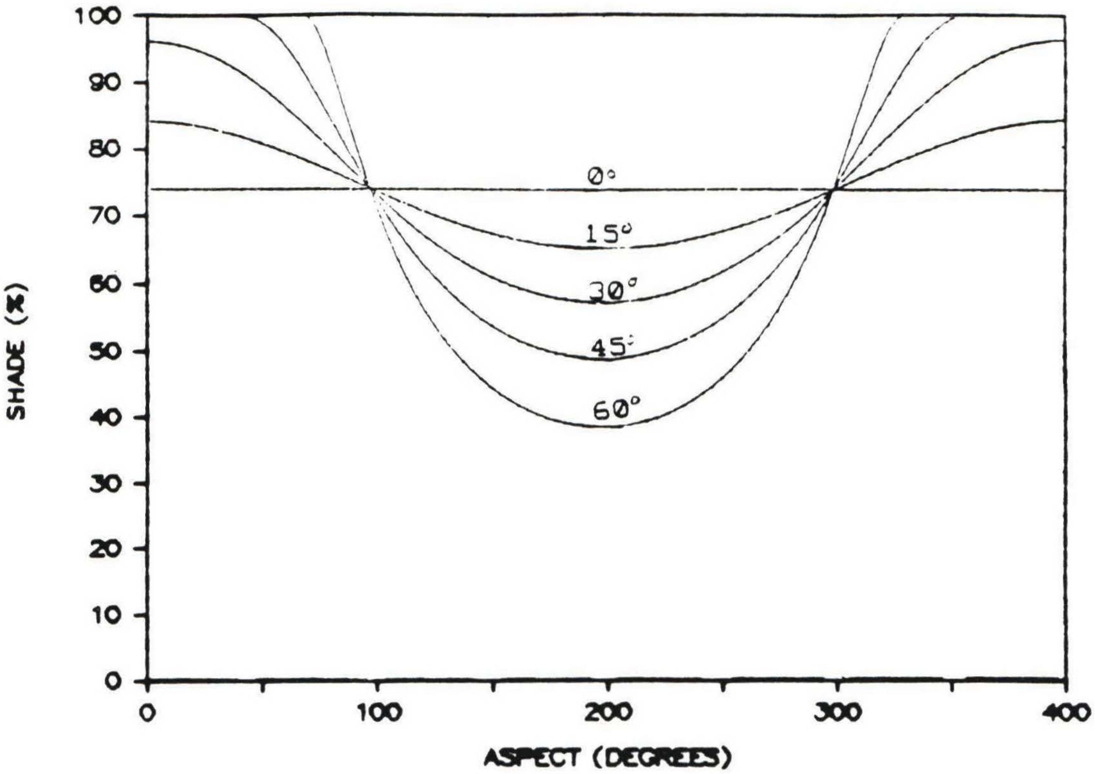


FIGURE B: SHADE BY ASPECT BY SLOPE ON DEC. 21

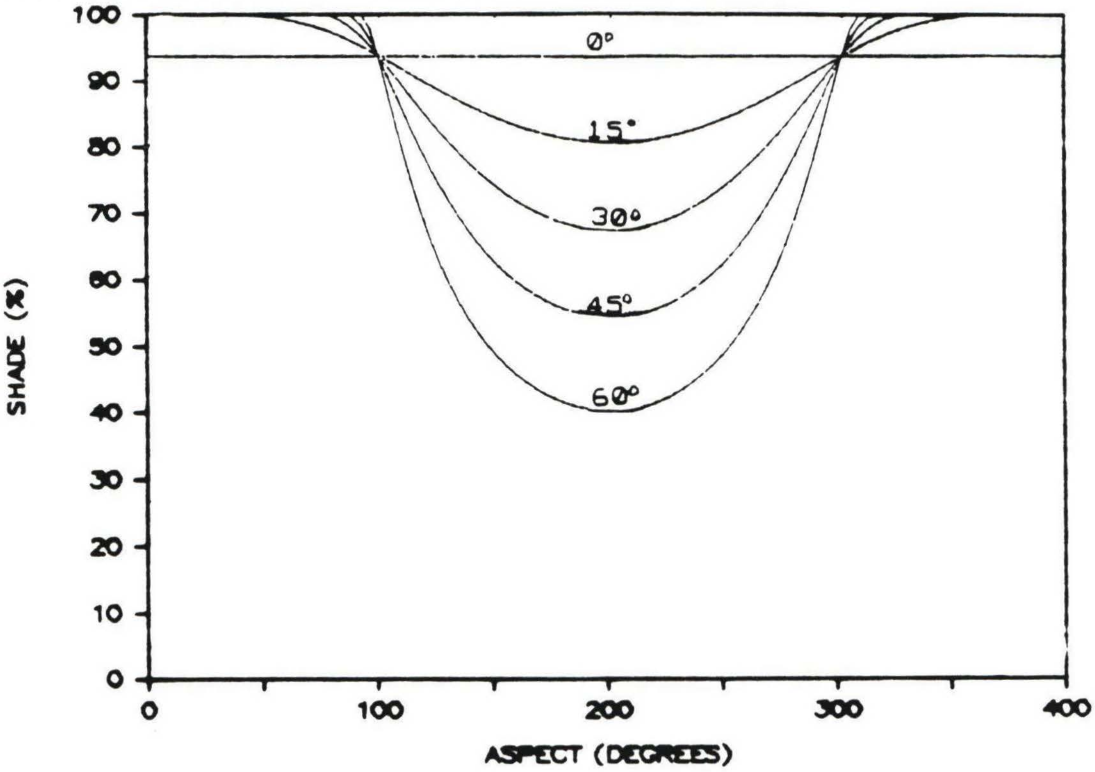


FIGURE A: SHADE BY ASPECT AND SLOPE WITH 20% CROWN CLOSURE

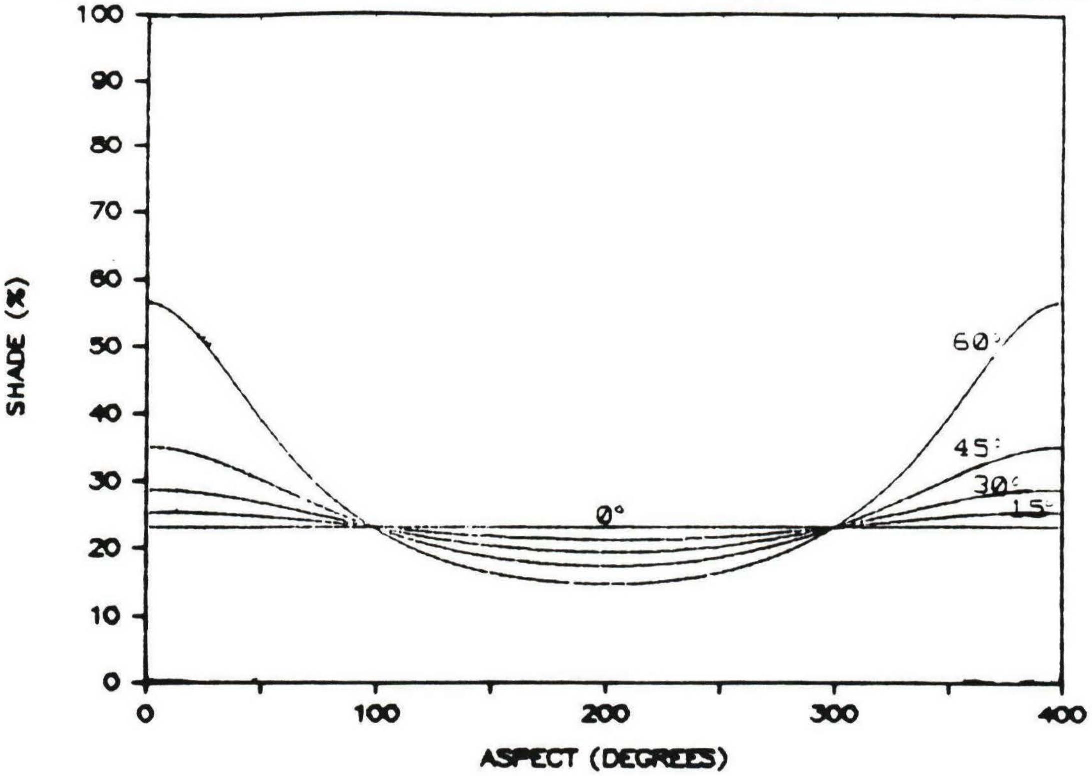


FIGURE B: SHADE BY ASPECT AND SLOPE WITH 75% CROWN CLOSURE

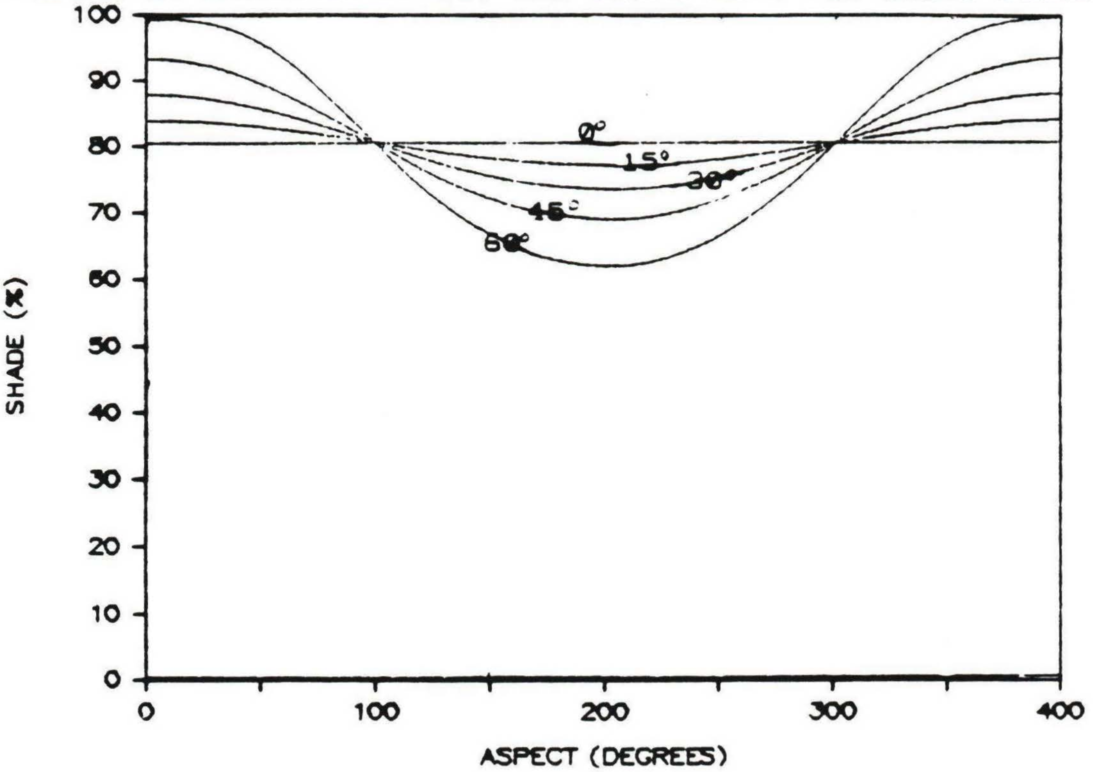


FIGURE A: SHADE BY TIME OF DAY AND MONTH AT 70 N. LATITUDE

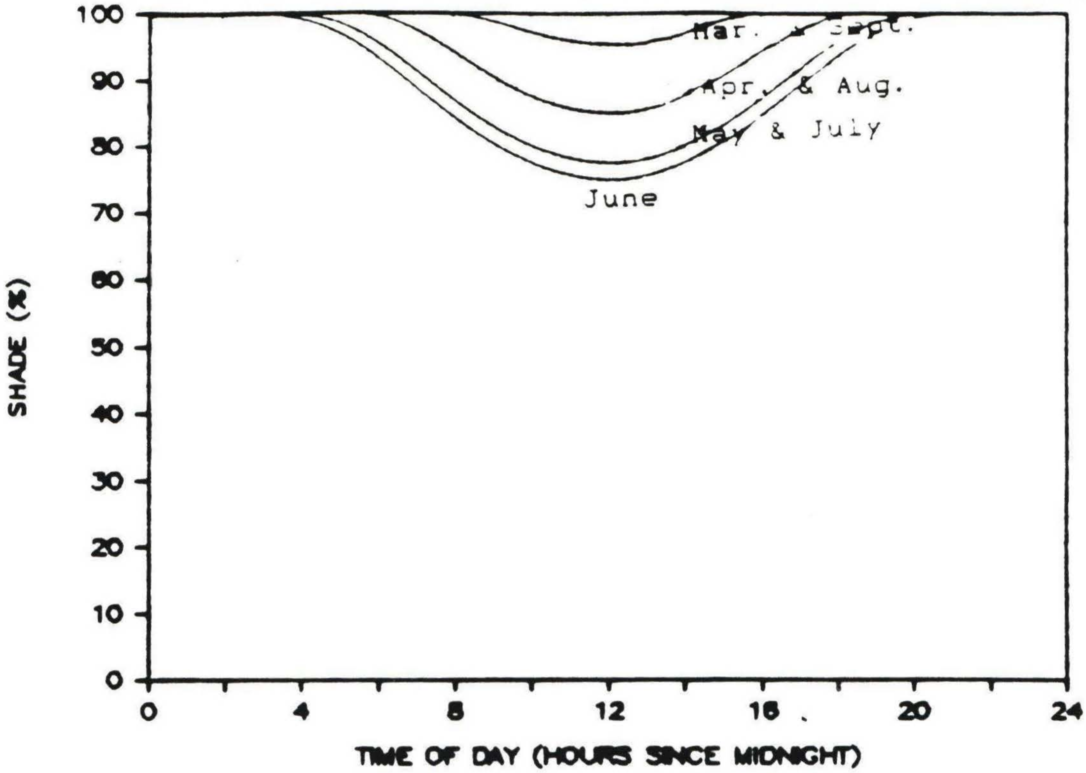


FIGURE B: SHADE BY TIME OF DAY AND MONTH FOR 20% CROWN CLOSURE AT 70 N. LATITUDE

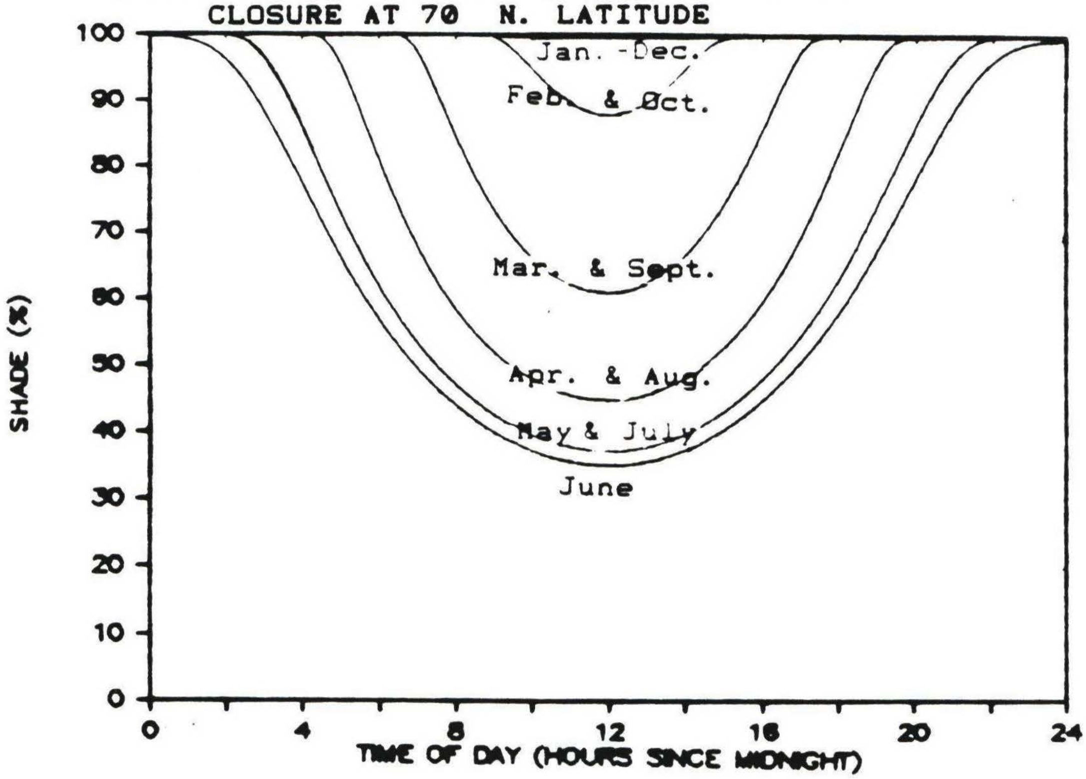


FIGURE A: SHADE BY TIME OF DAY AND MONTH AT 25 N. LATITUDE

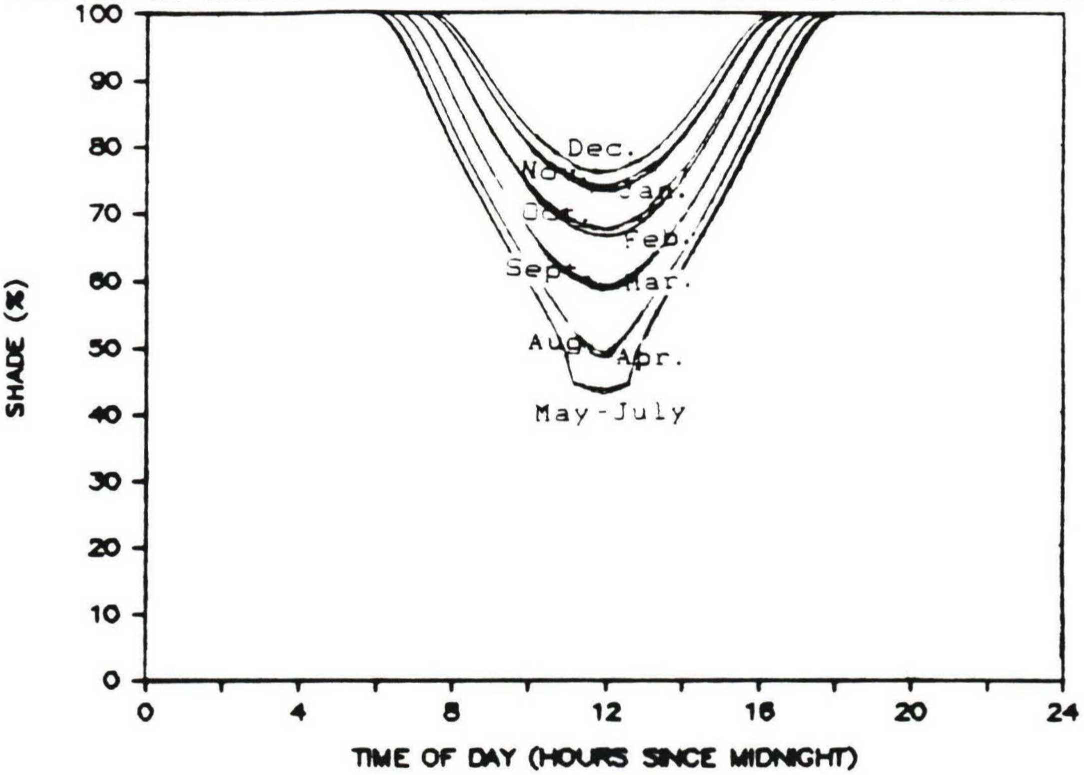


FIGURE B: SHADE BY TIME OF DAY AND MONTH FOR 150-FT TREES WITH 90-FT CROWN LENGTH AND CROWN RATIO 7.5

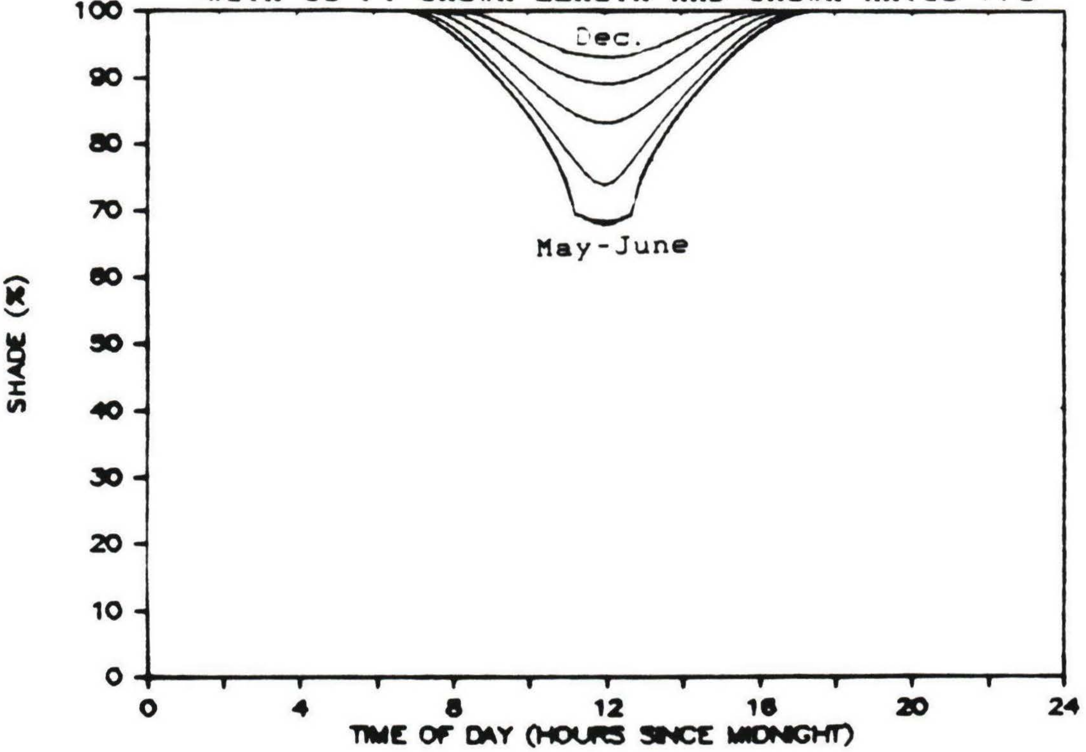


FIGURE A: SHADE BY TIME OF DAY AND MONTH FOR 100-FT TREES WITH 60-FT CROWN LENGTH

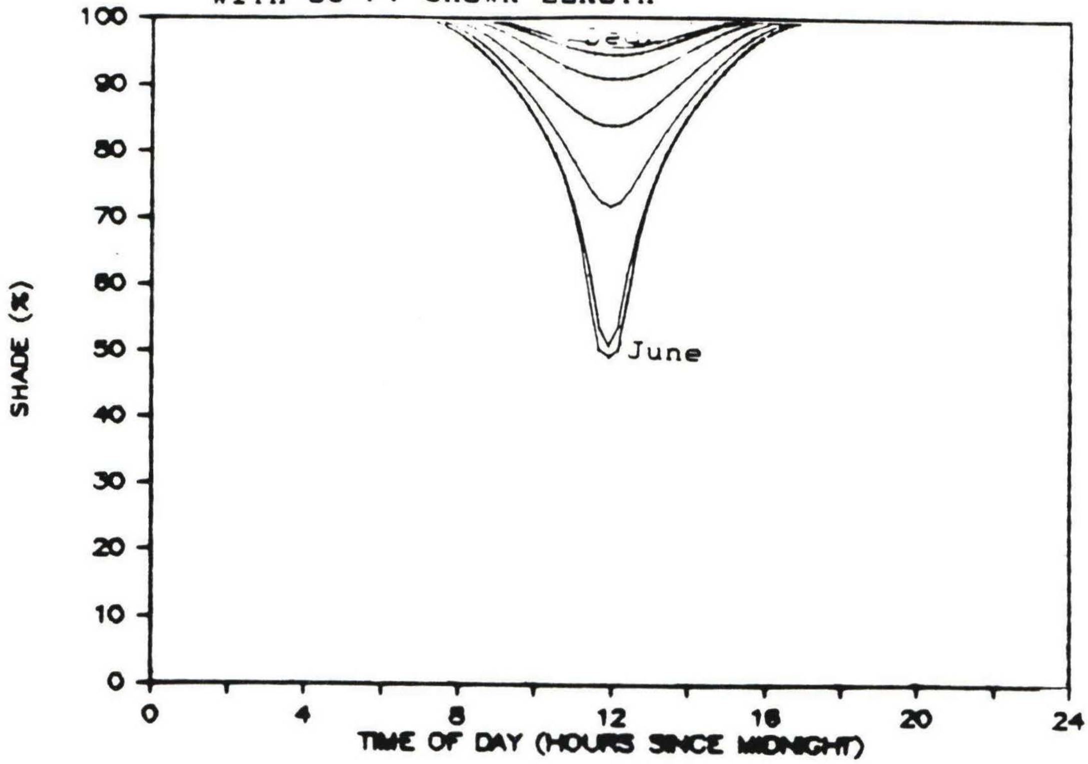
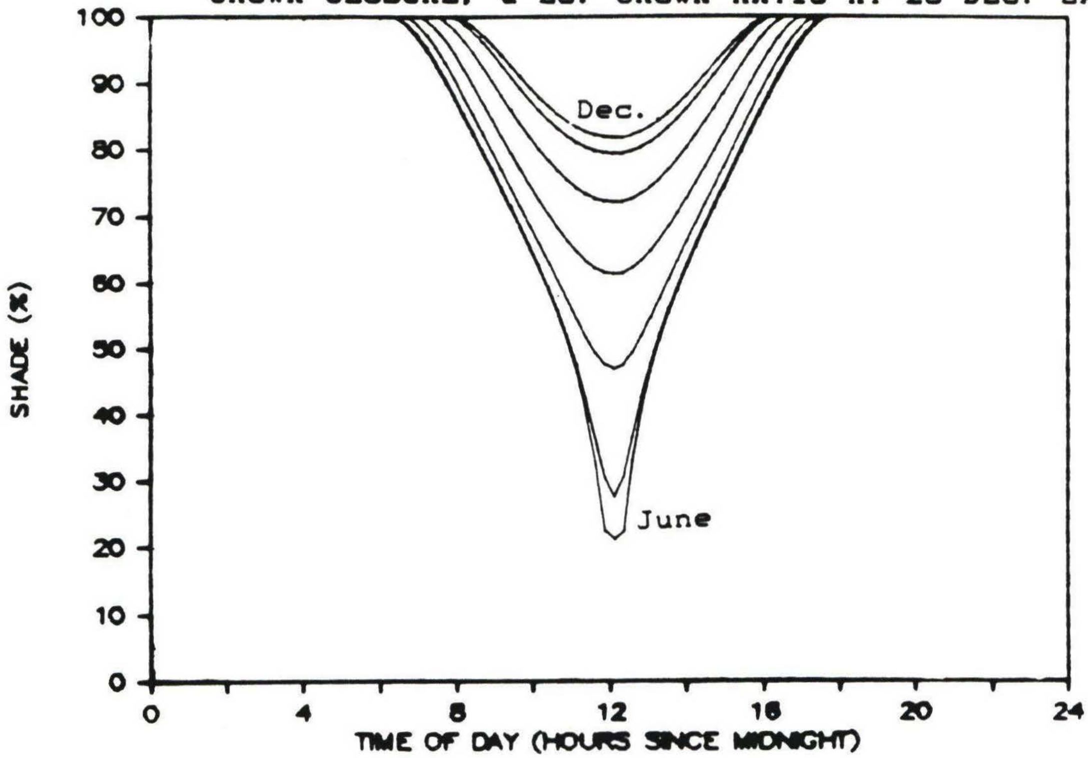


FIGURE B: SHADE BY TIME OF DAY & MONTH FOR TALL TREES, 20% CROWN CLOSURE, & LG. CROWN RATIO AT 25 DEG. LAT.



*APPENDIX 2

SENSITIVITY ANALYSIS OF SOLAR INTENSITY SUBCOMPONENT OF FINE FUEL MOISTURE

*Baseline values (Table 3) apply, except where otherwise noted.

FIGURE A: SOLAR INTENSITY BY SHADE AND HAZE
(ELEVATION 10,000 FT, SOLAR ANGLE 15 DEGREES)

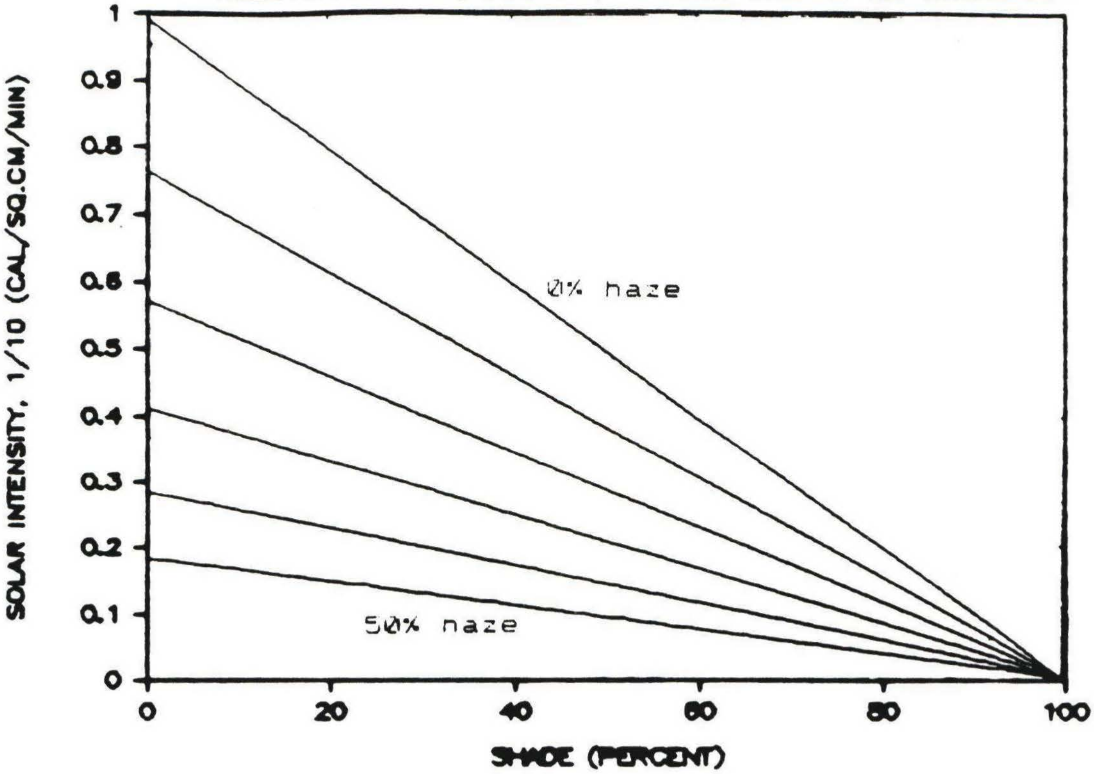


FIGURE B: SOLAR INTENSITY BY SHADE AND HAZE
(SOLAR ANGLE 30 DEGREES)

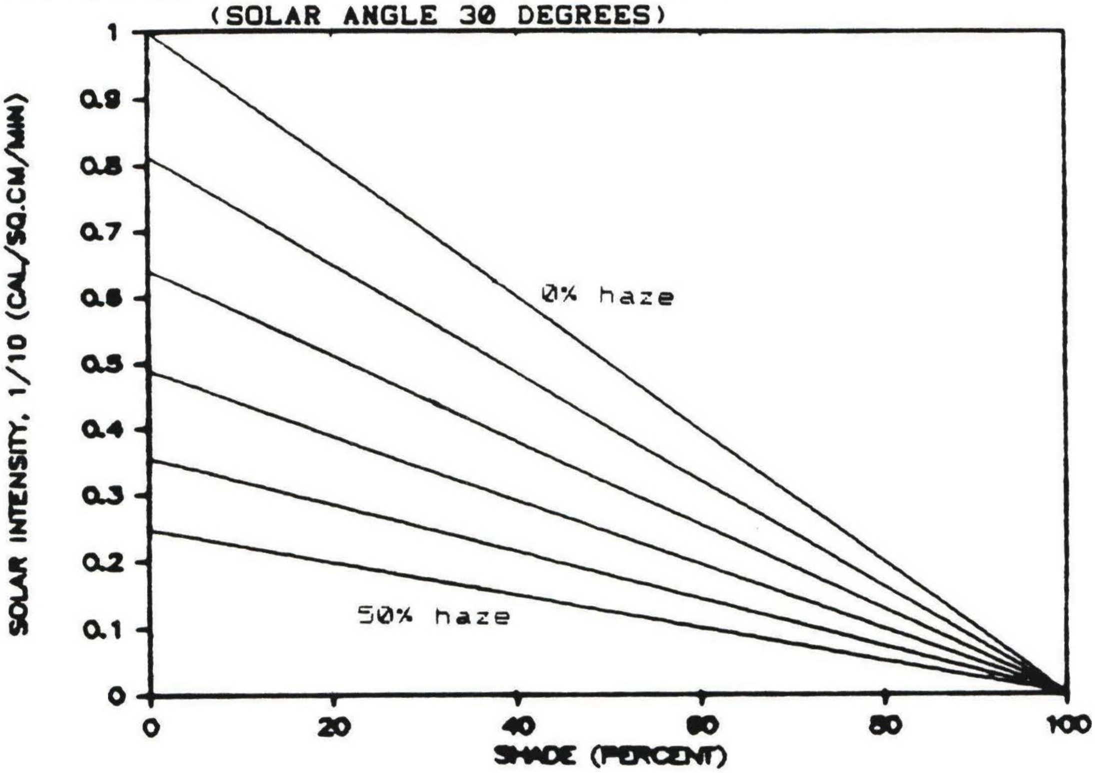


FIGURE A: SOLAR INTENSITY BY SHADE AND HAZE
(SOLAR ANGLE 45 DEGREES)

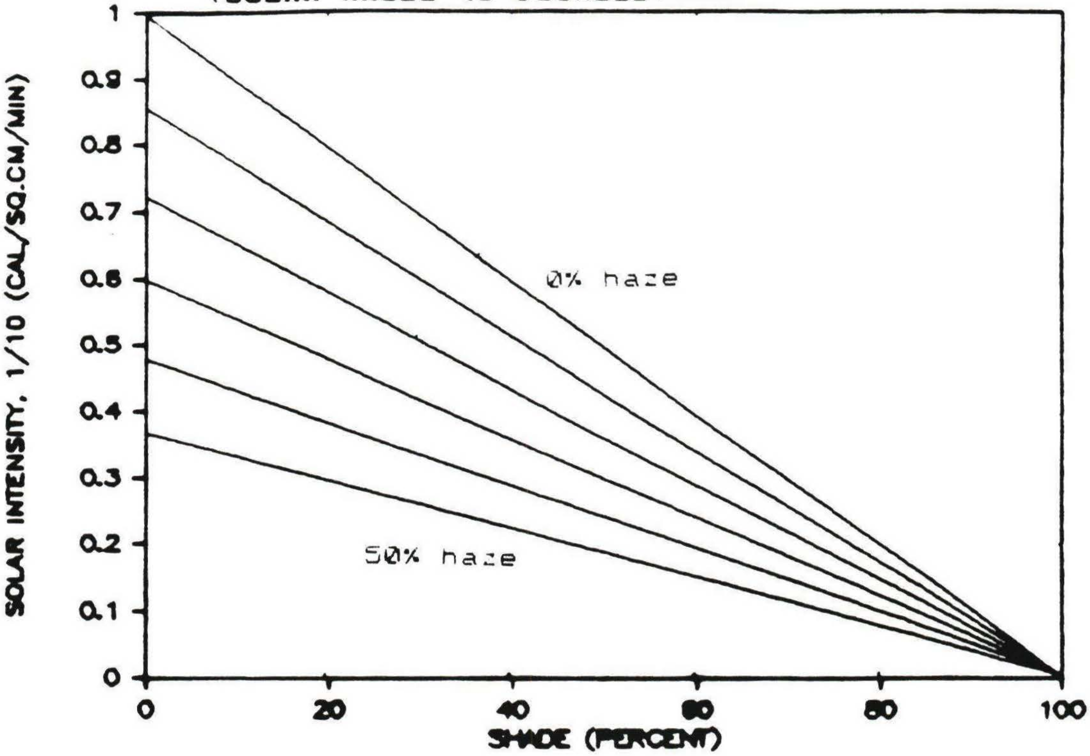


FIGURE B: SOLAR INTENSITY BY SHADE AND HAZE
(ELEVATION 5000 FT, SOLAR ANGLE 45 DEGREES)

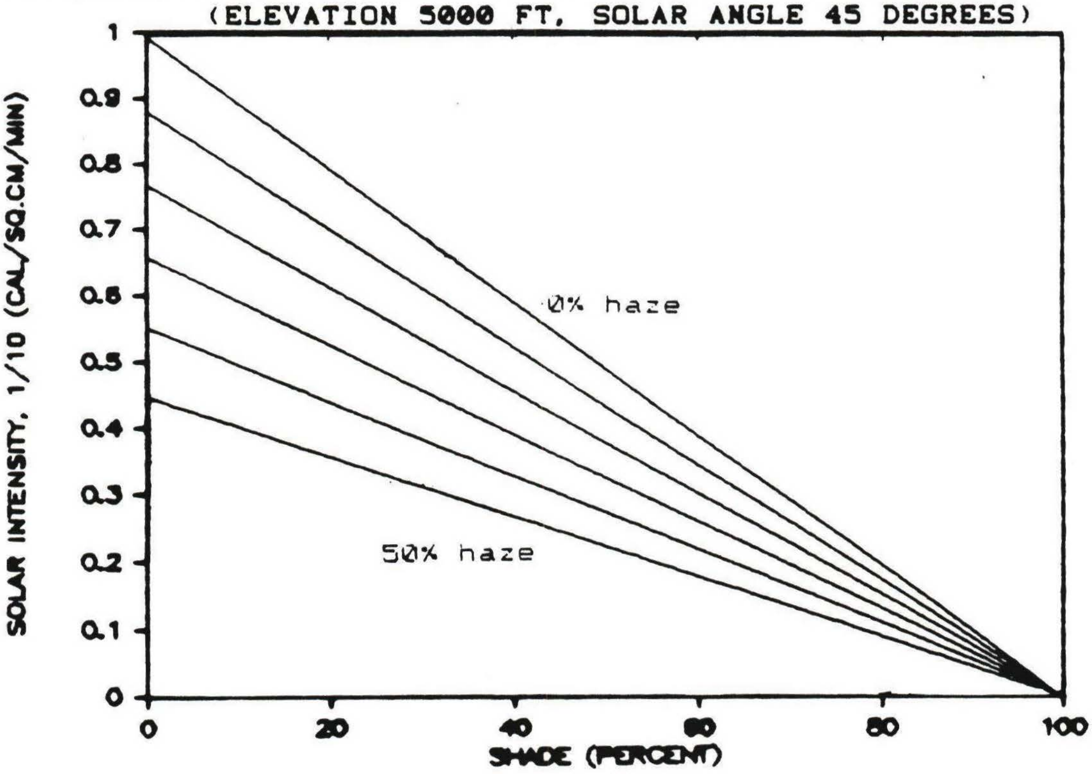


FIGURE A: SOLAR INTENSITY BY SHADE AND HAZE
(ELEVATION 10.000 FT. SOLAR ANGLE 45 DEGREES)

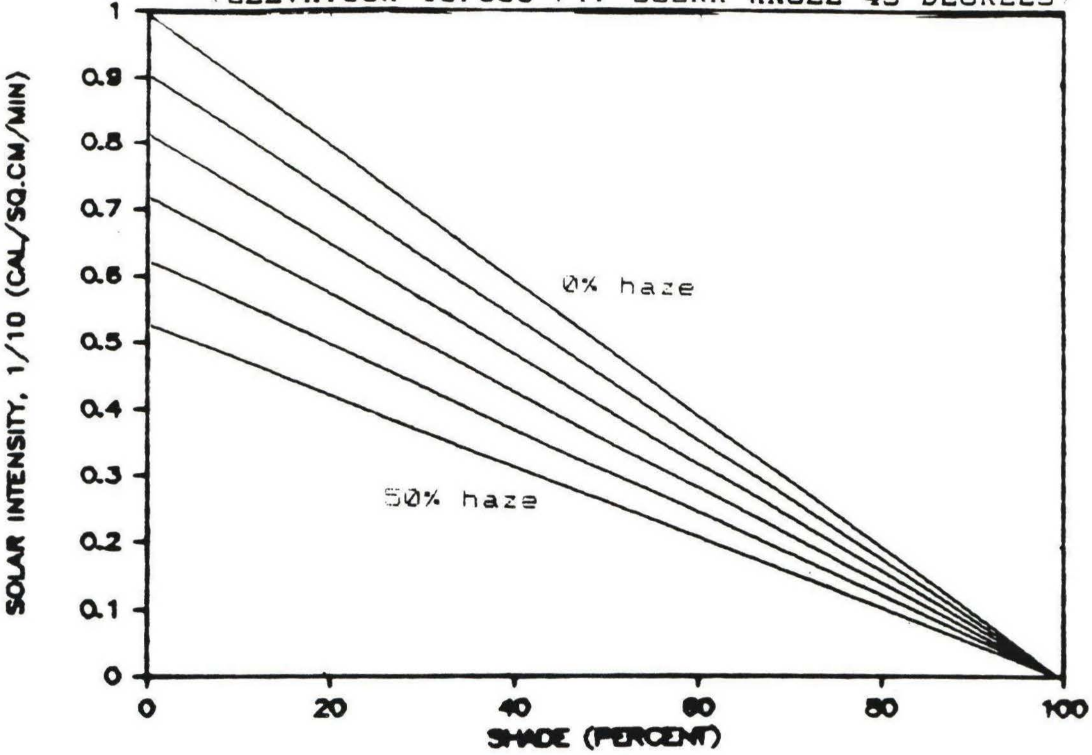


FIGURE B: SOLAR INTENSITY BY SHADE AND HAZE
(SOLAR ANGLE 60 DEGREES)

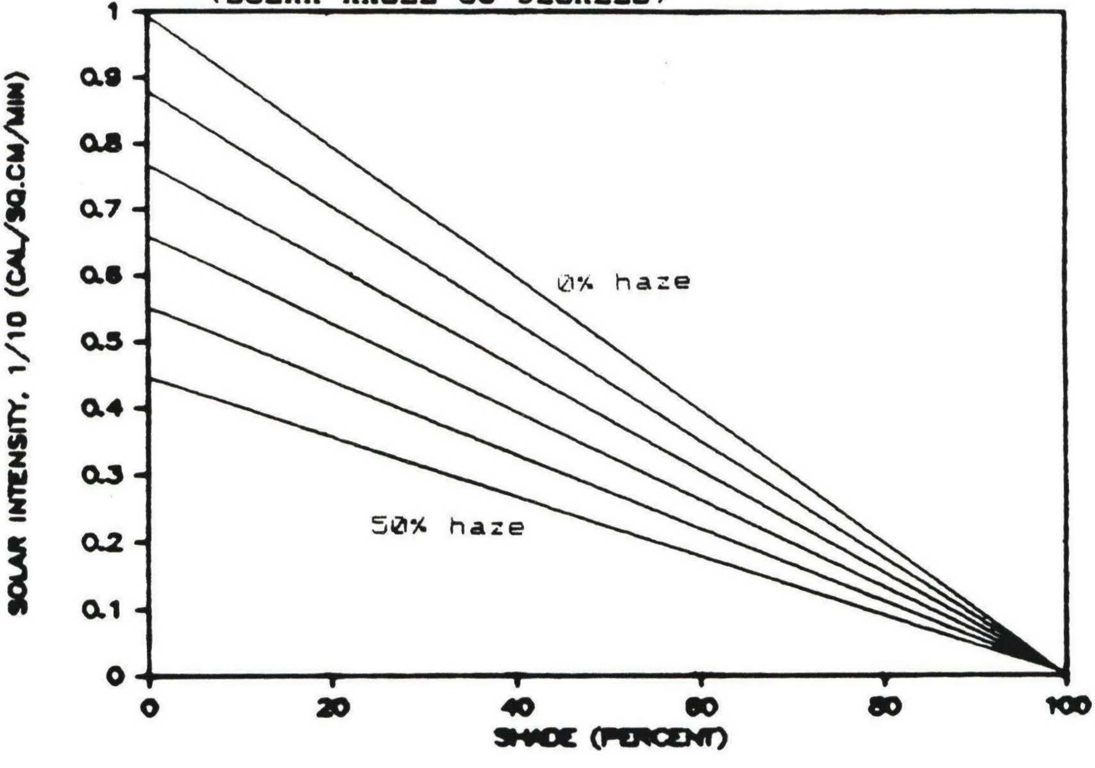


FIGURE A: SOLAR INTENSITY BY SHADE AND HAZE
(SOLAR ANGLE 75 DEGREES)

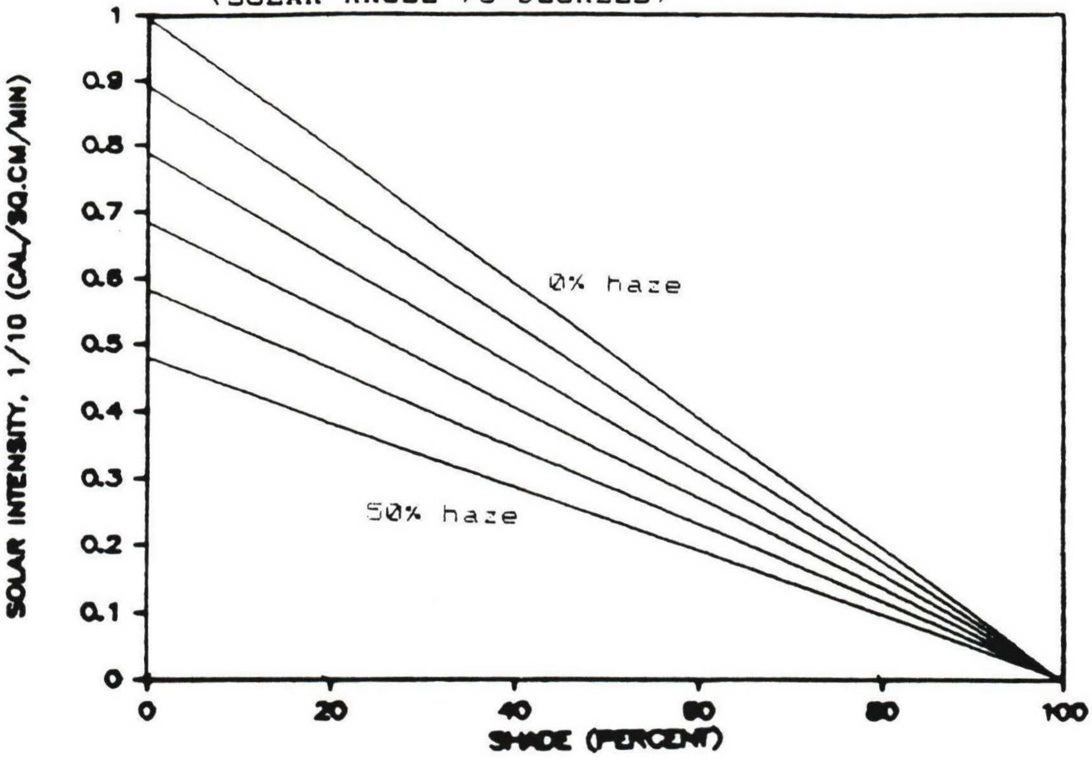


FIGURE B: SOLAR INTENSITY BY SHADE AND HAZE
(SOLAR ANGLE 90 DEGREES)

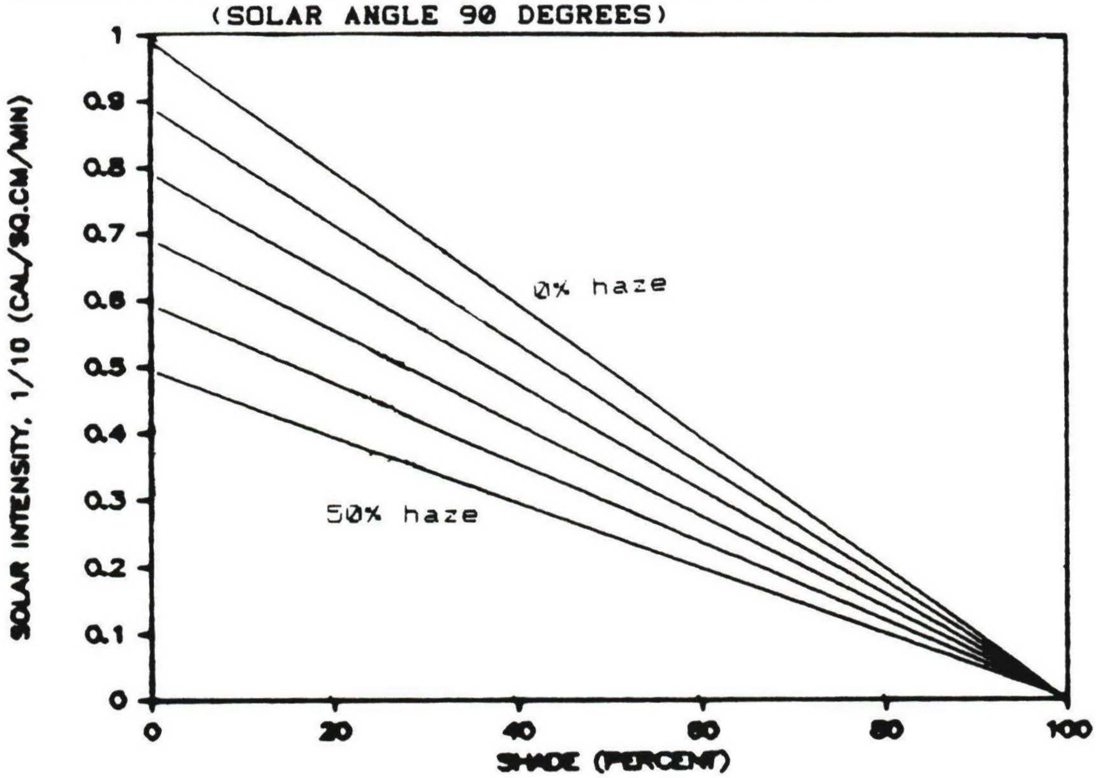


FIGURE A: SOLAR INTENSITY BY SHADE AND HAZE
(ELEVATION 10,000 FT. SOLAR ANGLE 90 DEGREES)

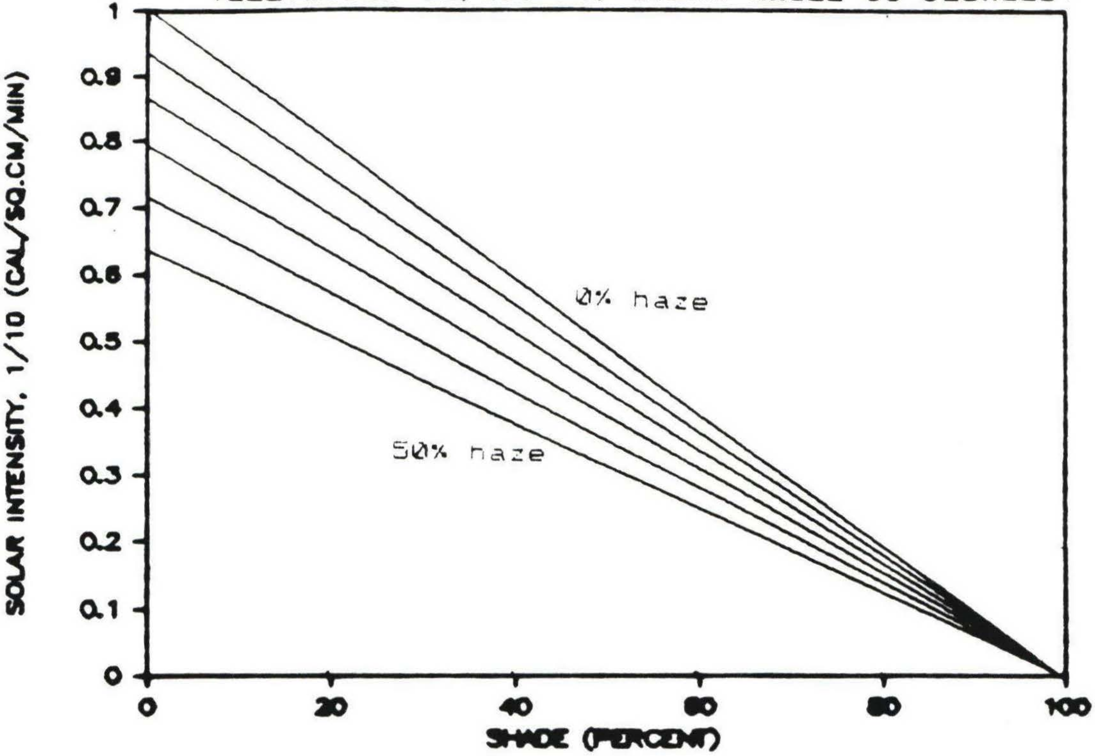


FIGURE B: SOLAR INTENSITY BY ELEVATION AND SOLAR ANGLE
(SHADE 50%, HAZE 25.5%)

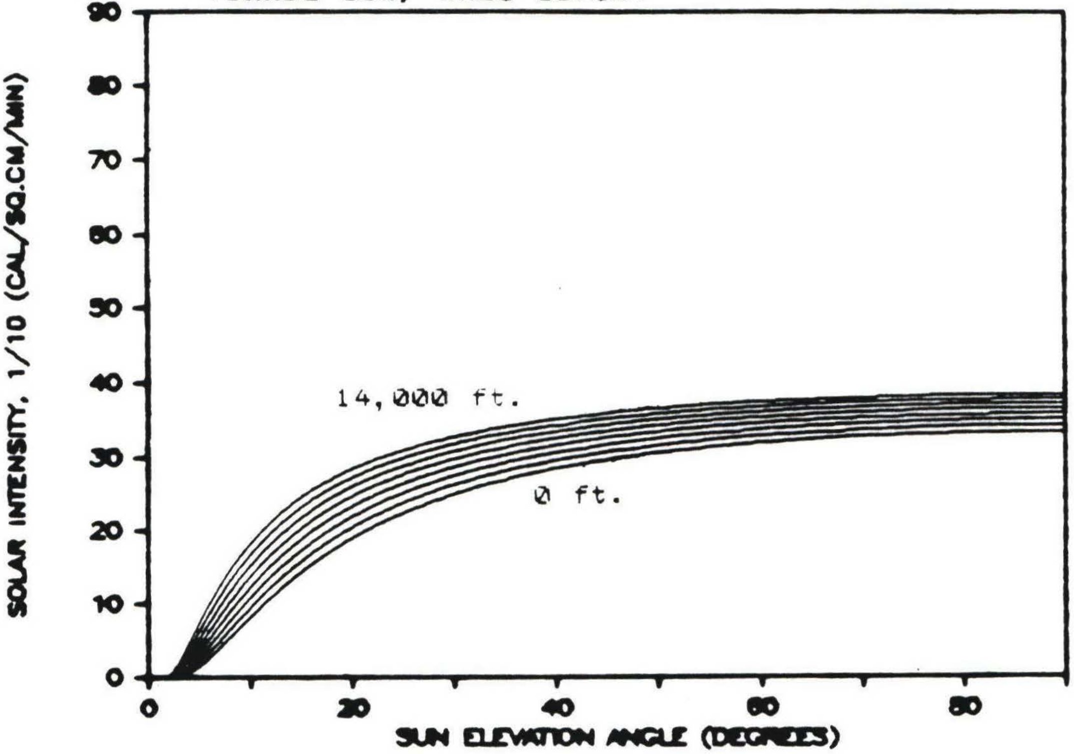


FIGURE A: SOLAR INTENSITY BY ELEVATION AND SOLAR ANGLE
(HAZE 5%, SHADE 0%)

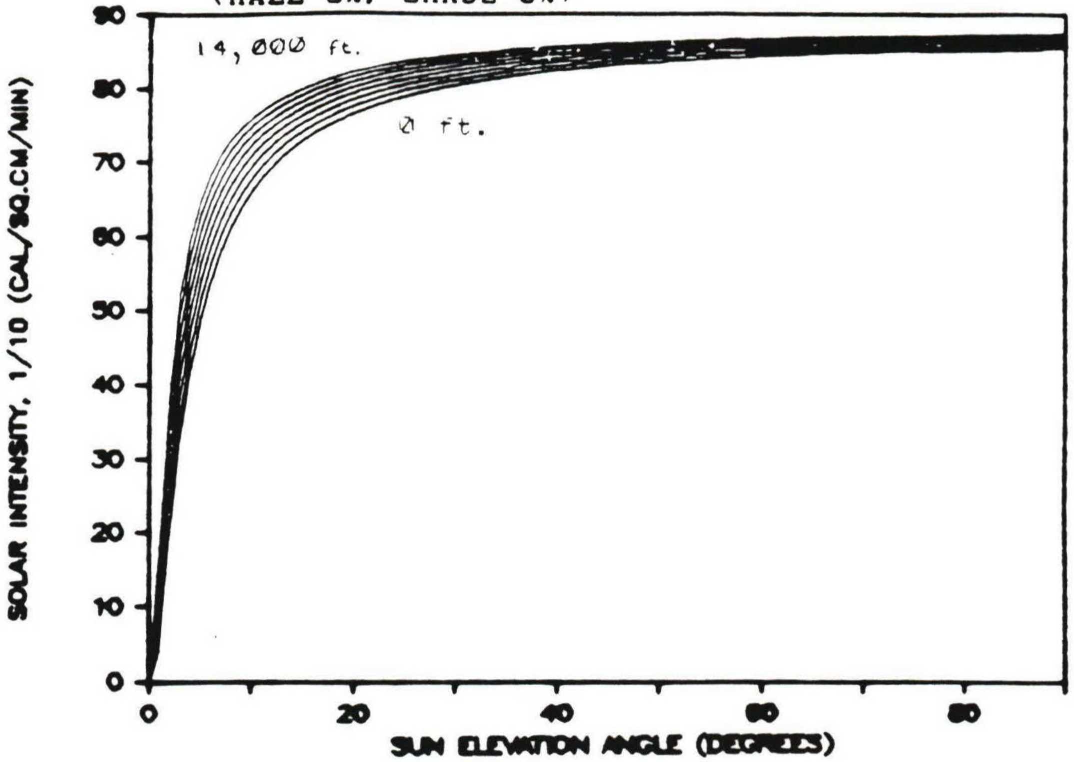


FIGURE B: SOLAR INTENSITY BY ELEVATION BY SOLAR ANGLE
(HAZE 20%, SHADE 0%)

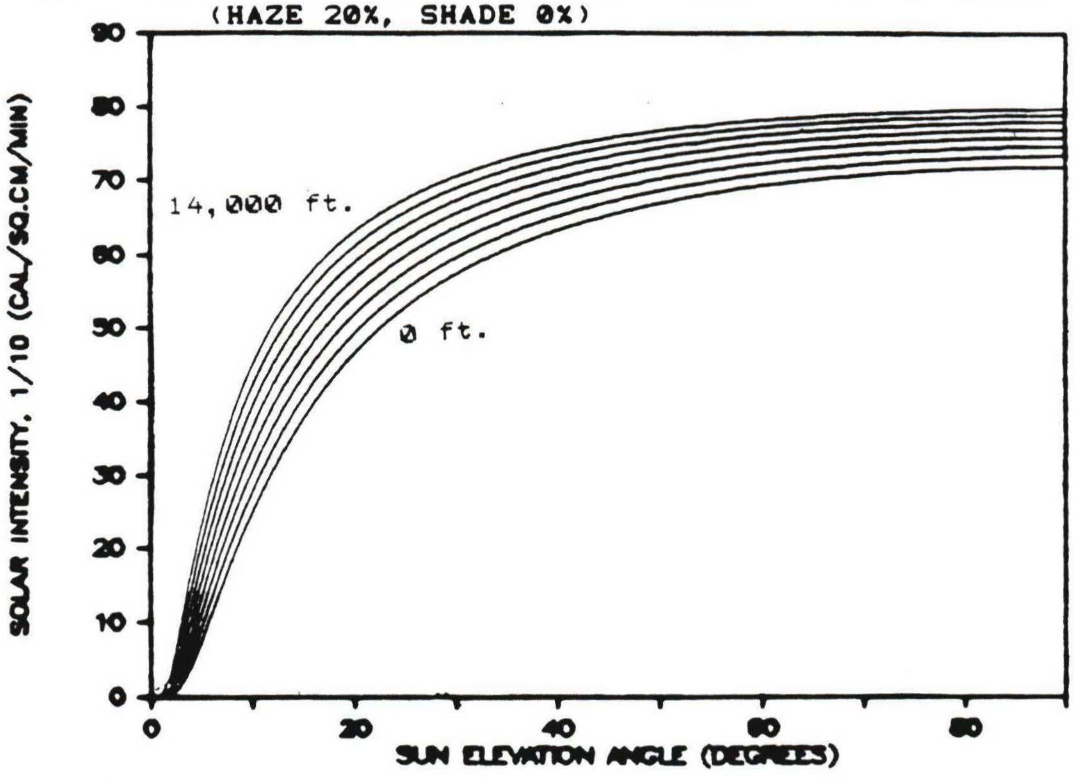


FIGURE A: SOLAR INTENSITY BY ELEVATION AND SOLAR ANGLE
(HAZE 25.5%, SHADE 0%)

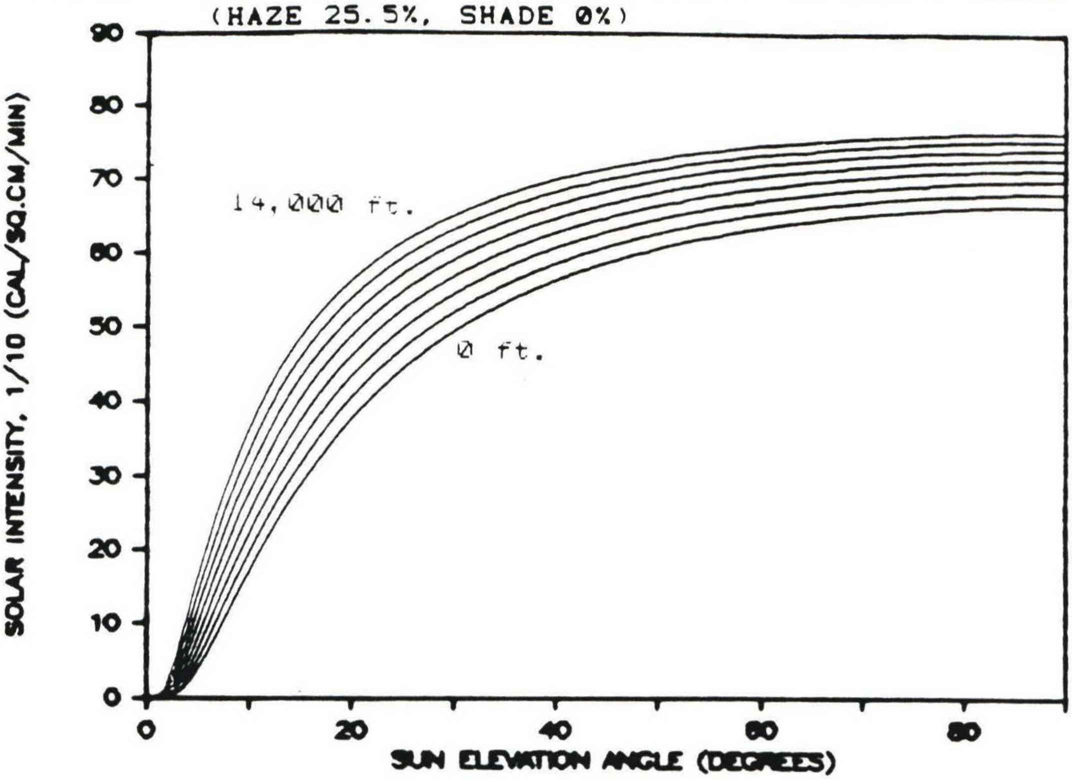
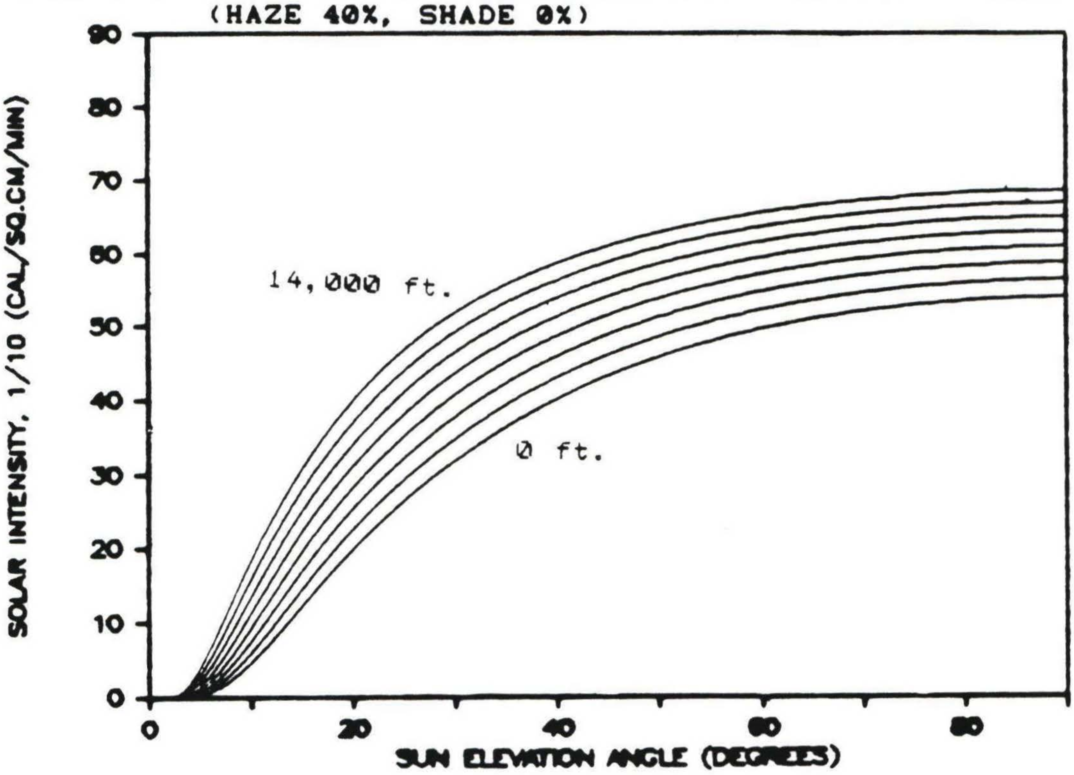


FIGURE B: SOLAR INTENSITY BY ELEVATION AND SOLAR ANGLE
(HAZE 40%, SHADE 0%)



*APPENDIX 3

SENSITIVITY ANALYSIS OF FUEL TEMPERATURE RISE COMPONENT

OF FINE FUEL MOISTURE

*Baseline values (Table 3) apply, except where otherwise noted.

FIGURE A: FUEL TEMP. RISE BY SOLAR INTENSITY AND WINDSPEED
(FUEL HEIGHT 0.1 FT)

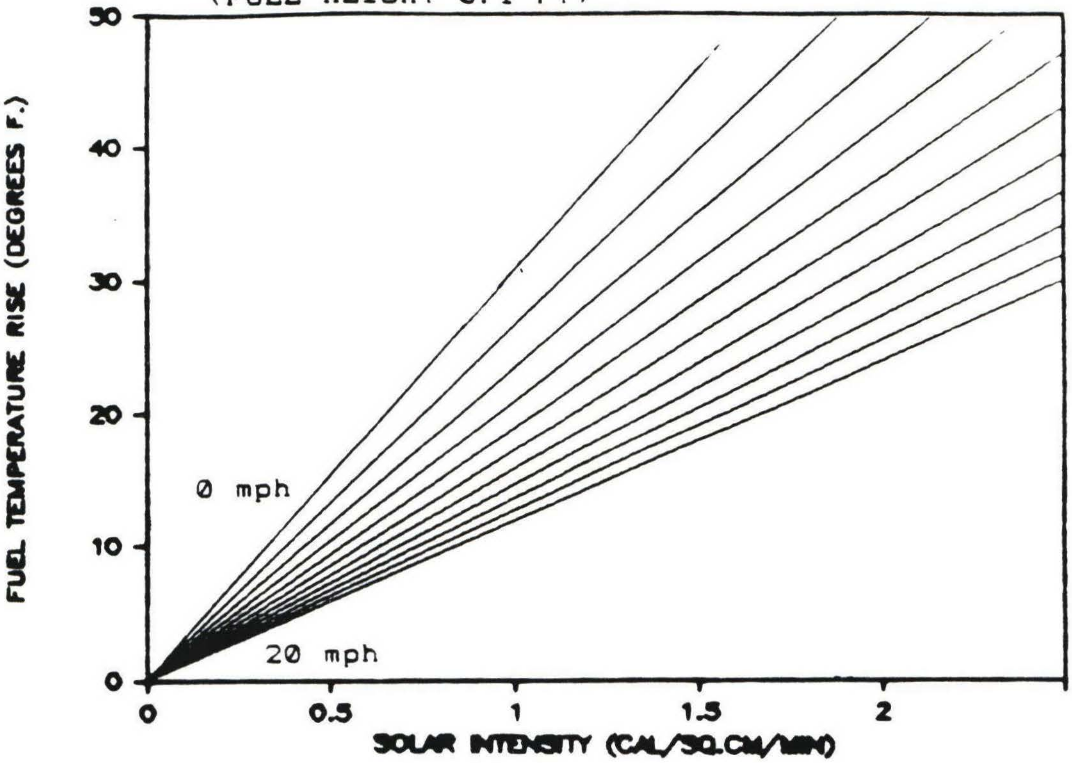


FIGURE B: FUEL TEMP. RISE BY SOLAR INTENSITY AND WINDSPEED
(FUEL HEIGHT 1 FT)

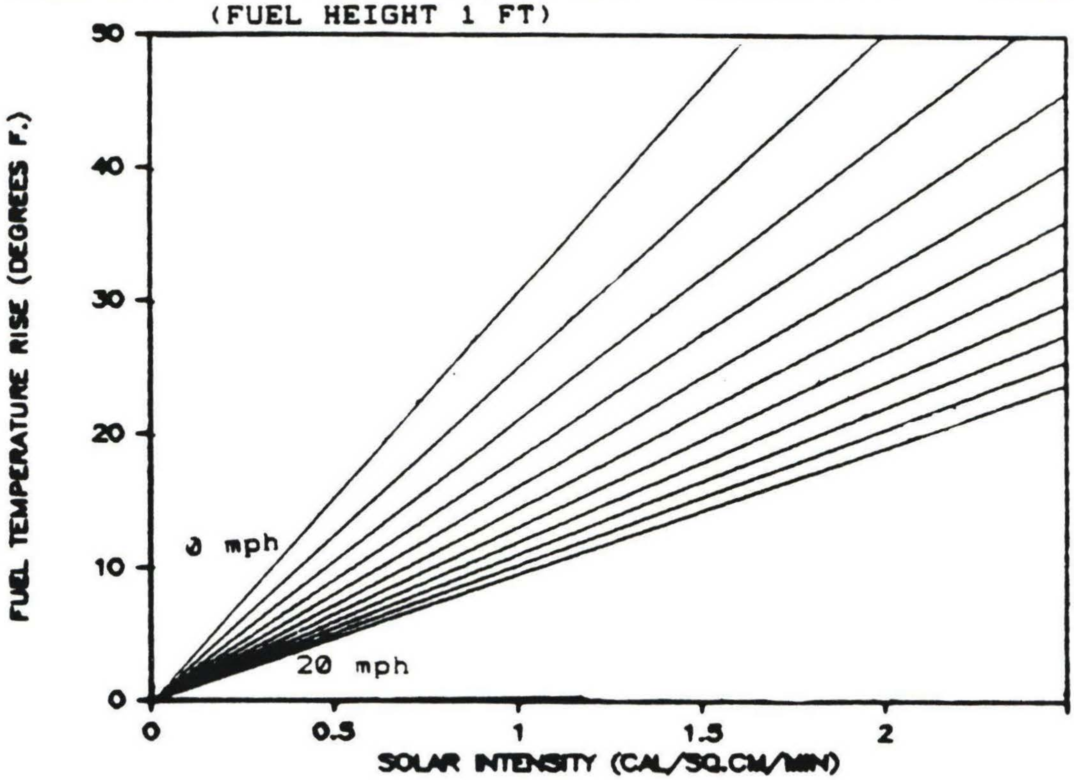


FIGURE A: FUEL TEMP. RISE BY SOLAR INTENSITY AND WINDSPEED
(FUEL HEIGHT 10 FT)

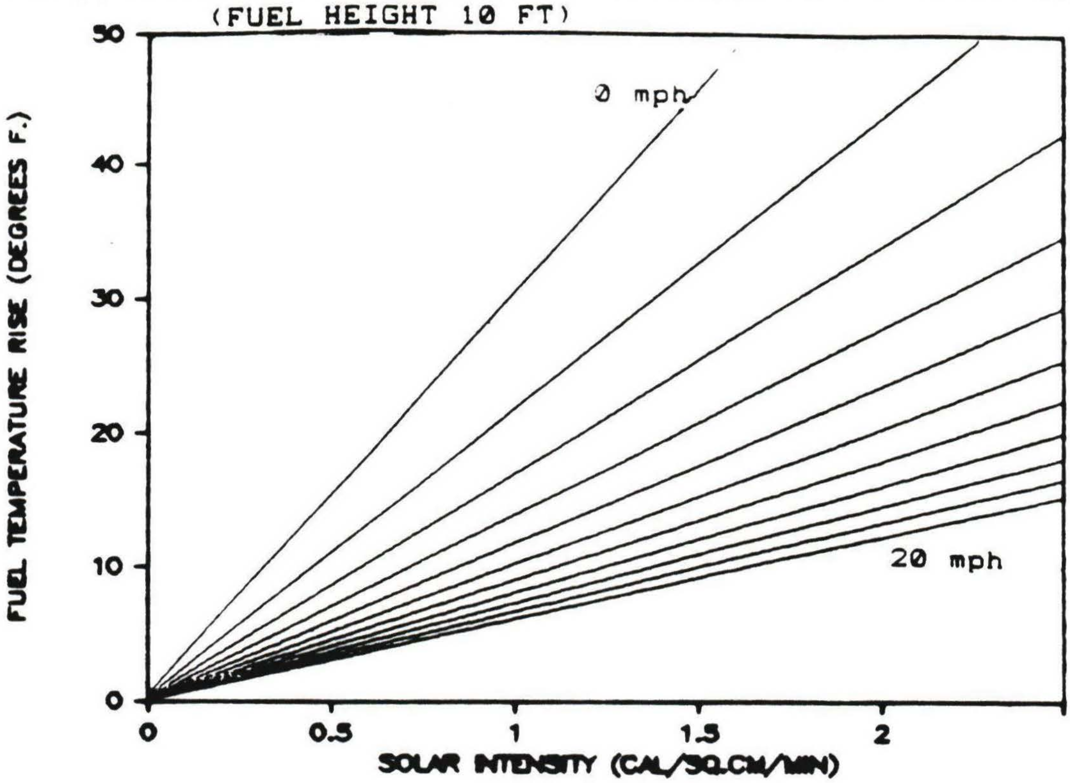


FIGURE B: FUEL TEMP. RISE BY WINDSPEED AND FUEL HEIGHT
(SOLAR INTENSITY 1.0 CAL/SQ.CM/MIN)

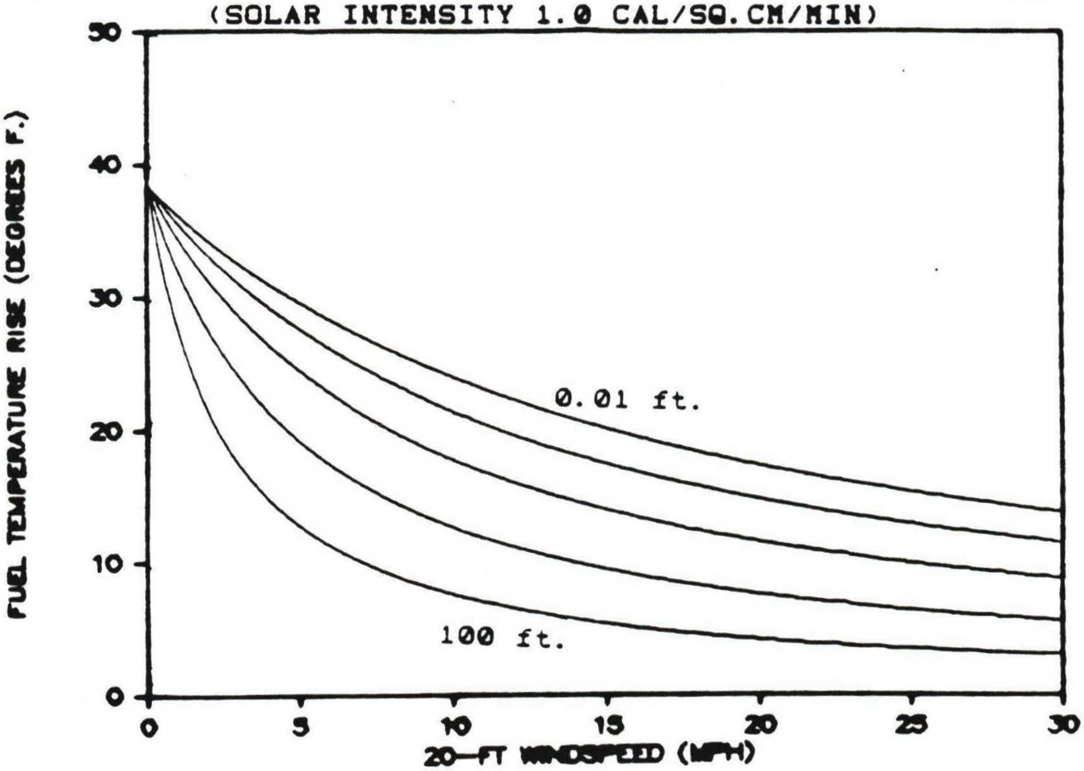


FIGURE A: FUEL TEMP. RISE BY WINDSPEED AND FUEL HEIGHT
(SOLAR INTENSITY 1.5 CAL/SQ.CM/MIN)

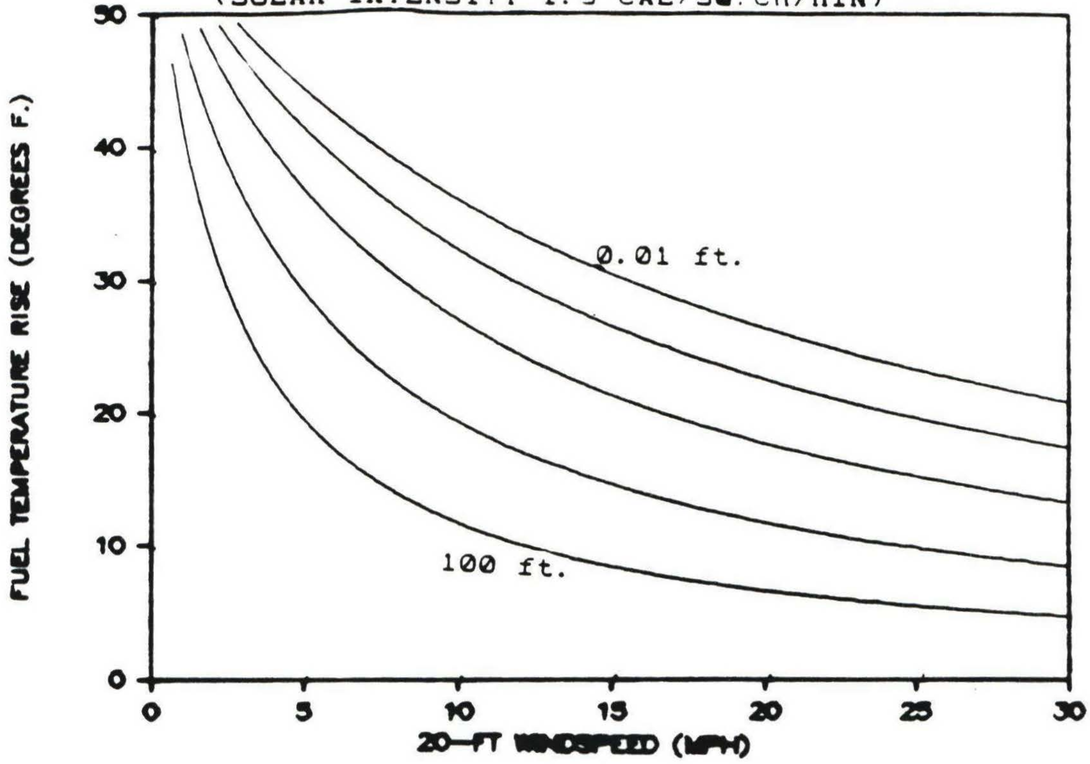
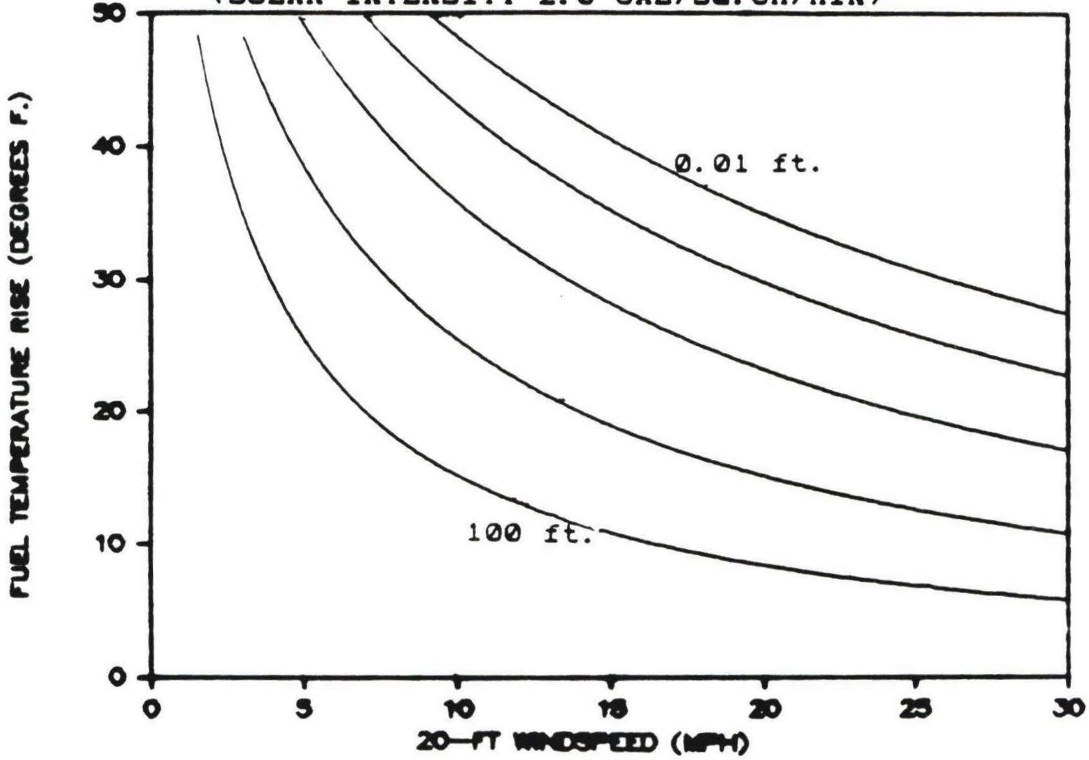


FIGURE B: FUEL TEMP. RISE BY WINDSPEED AND FUEL HEIGHT
(SOLAR INTENSITY 2.0 CAL/SQ.CM/MIN)



*APPENDIX 4

SENSITIVITY ANALYSIS OF FINE FUEL MOISTURE

*Baseline values (Table 3) apply, except where otherwise noted.

FIGURE A: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 1 MPH, FUEL TEMP. 75 DEGREES)

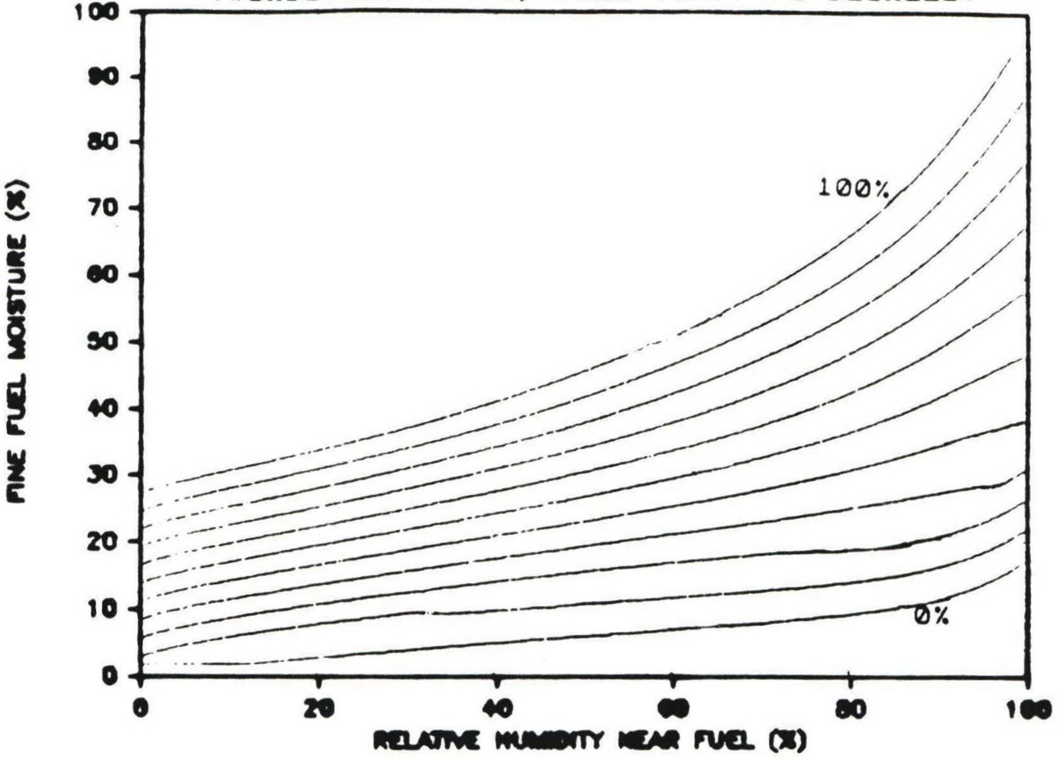


FIGURE B: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 5 MPH, FUEL TEMP. 75 DEGREES)

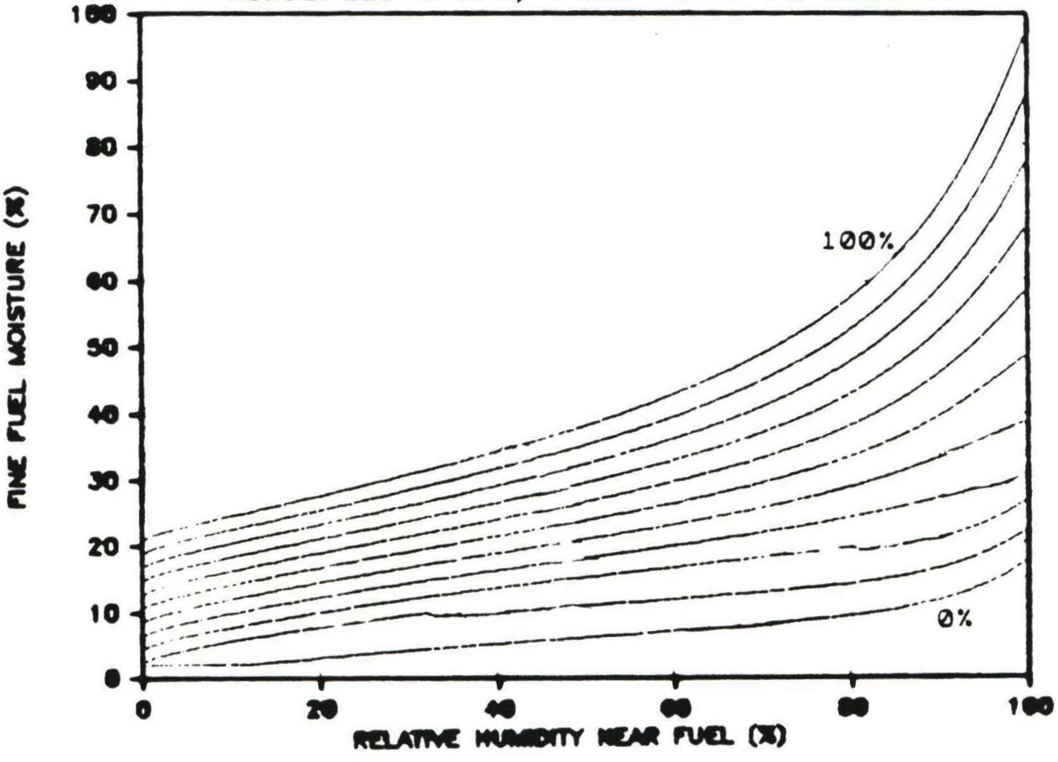


FIGURE A: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 15 MPH, FUEL TEMP. 75 DEGREES)

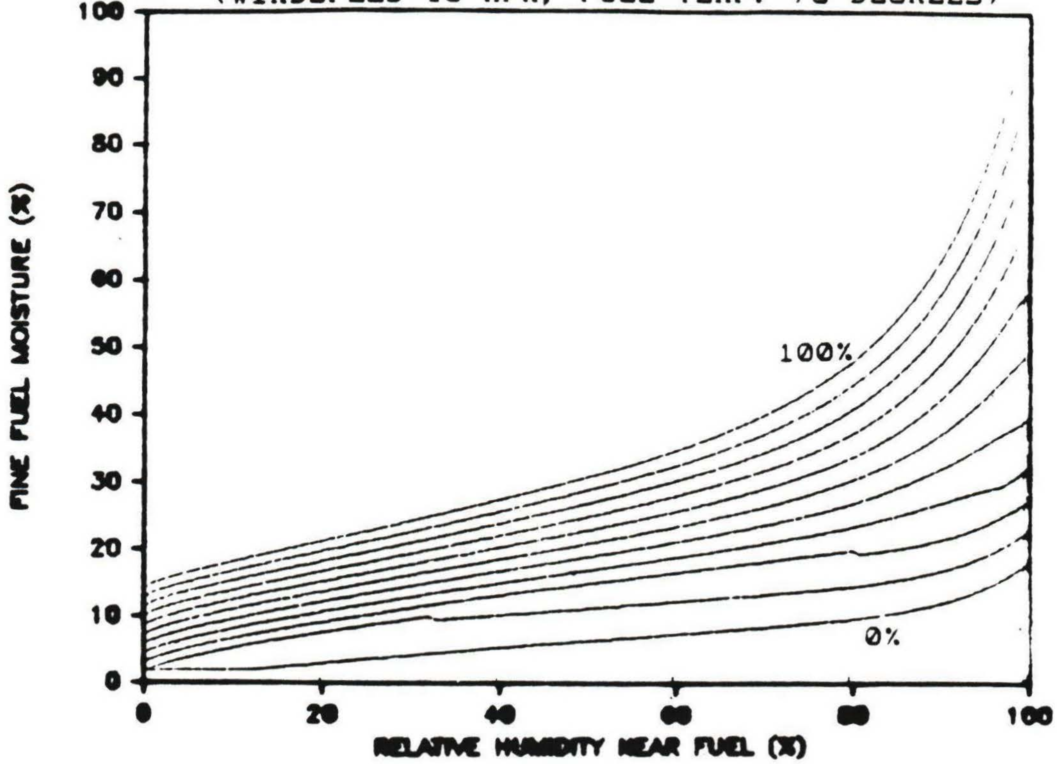


FIGURE B: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 5 MPH, FUEL TEMP. 95 DEGREES)

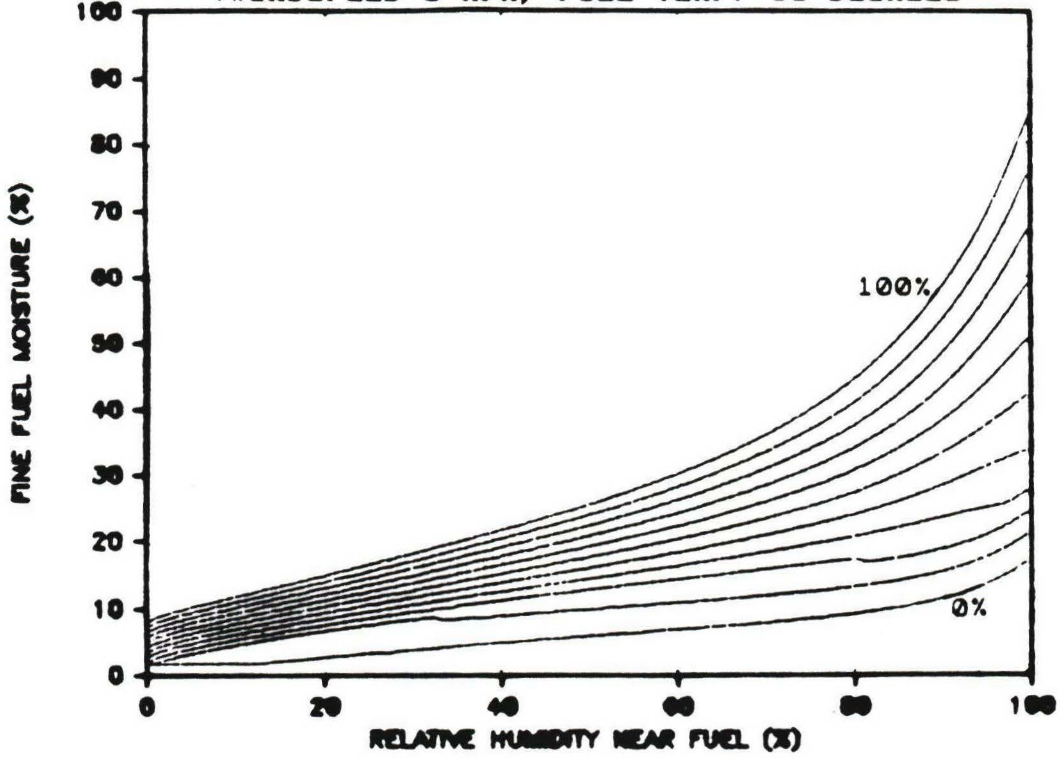


FIGURE A: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 5 MPH, FUEL TEMP. 100 DEGREES)

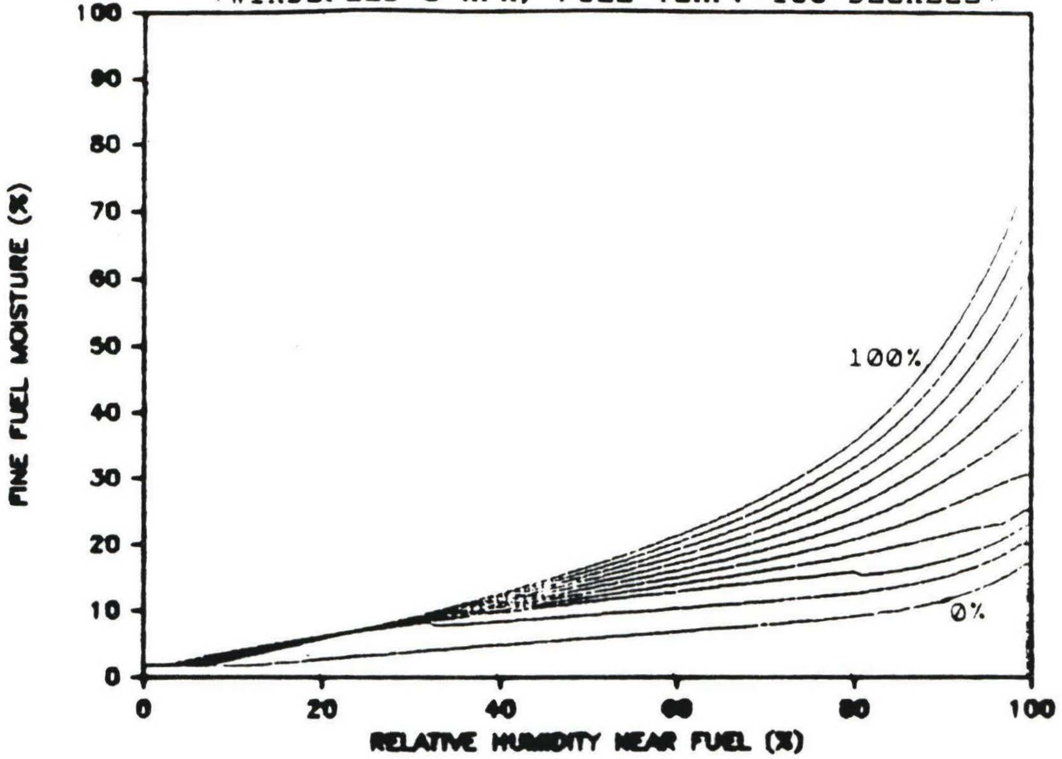


FIGURE B: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 15 MPH, FUEL TEMP. 120 DEGREES)

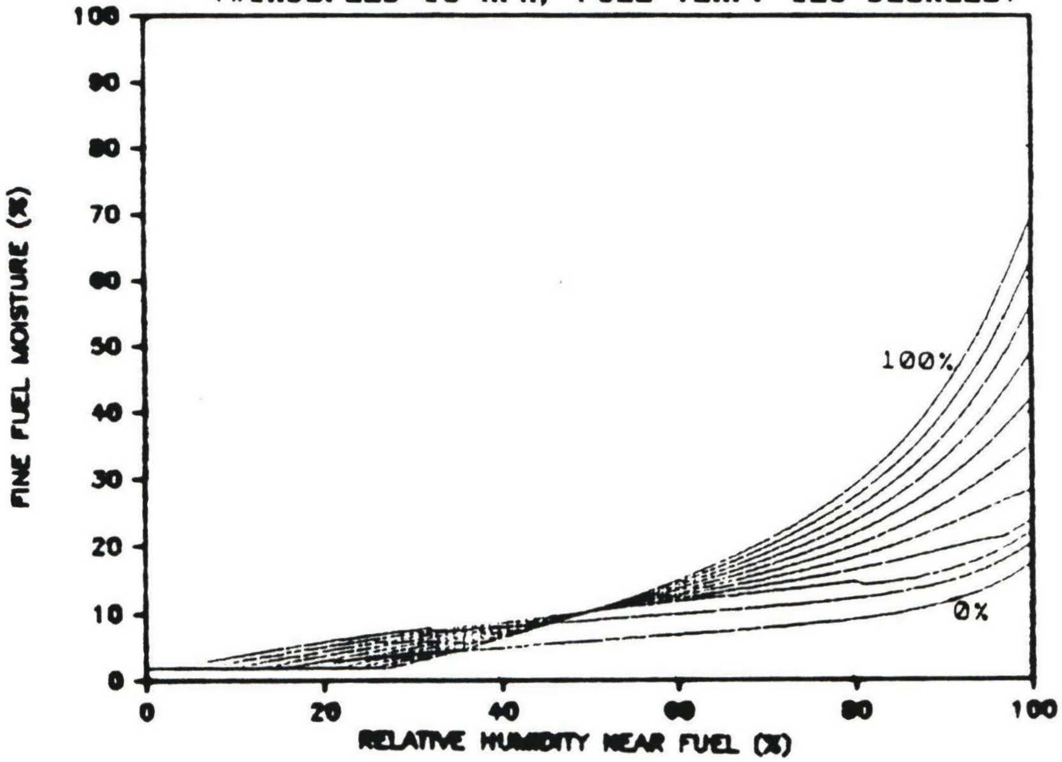


FIGURE A: FFM BY FUEL RH AND INITIAL FUEL MOISTURE
(WINDSPEED 15 MPH, FUEL TEMP. 120 DEGREES)

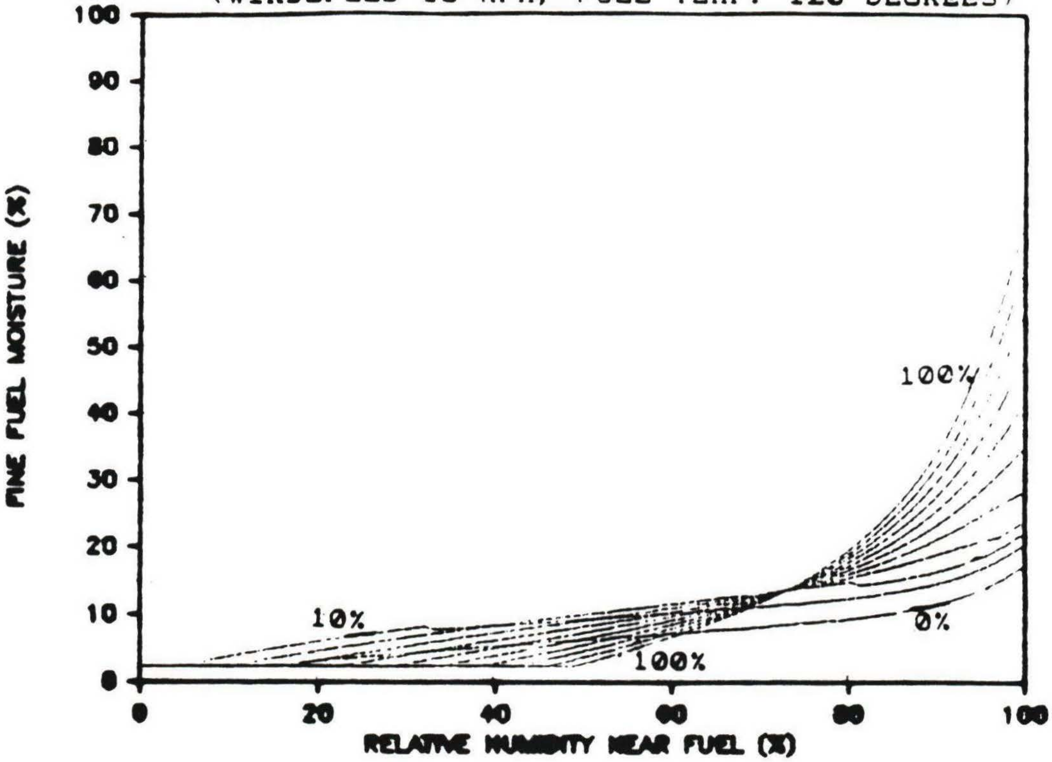


FIGURE B: FFM BY RAINFALL AND INITIAL FUEL MOISTURE
(FUEL TEMP. 75 DEGREES, FUEL RH 50%)

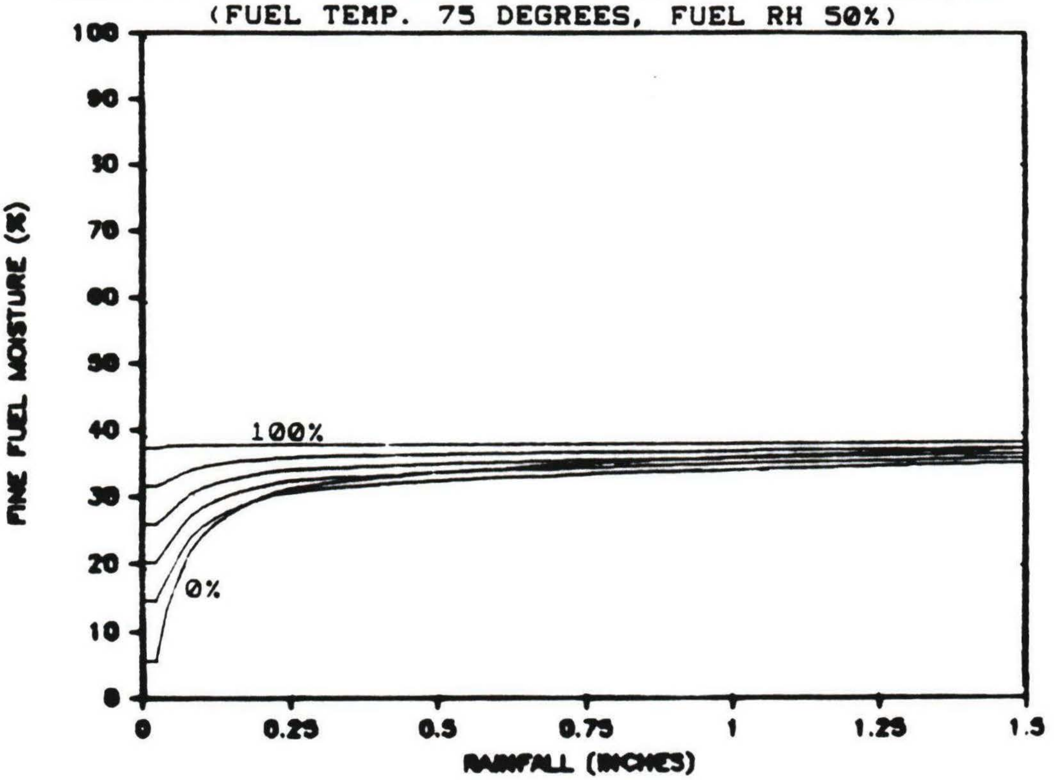


FIGURE A: FFM BY RAINFALL AND INITIAL FUEL MOISTURE
(FUEL TEMP. 75 DEG., FUEL RH 75%, WIND 1 MPH)

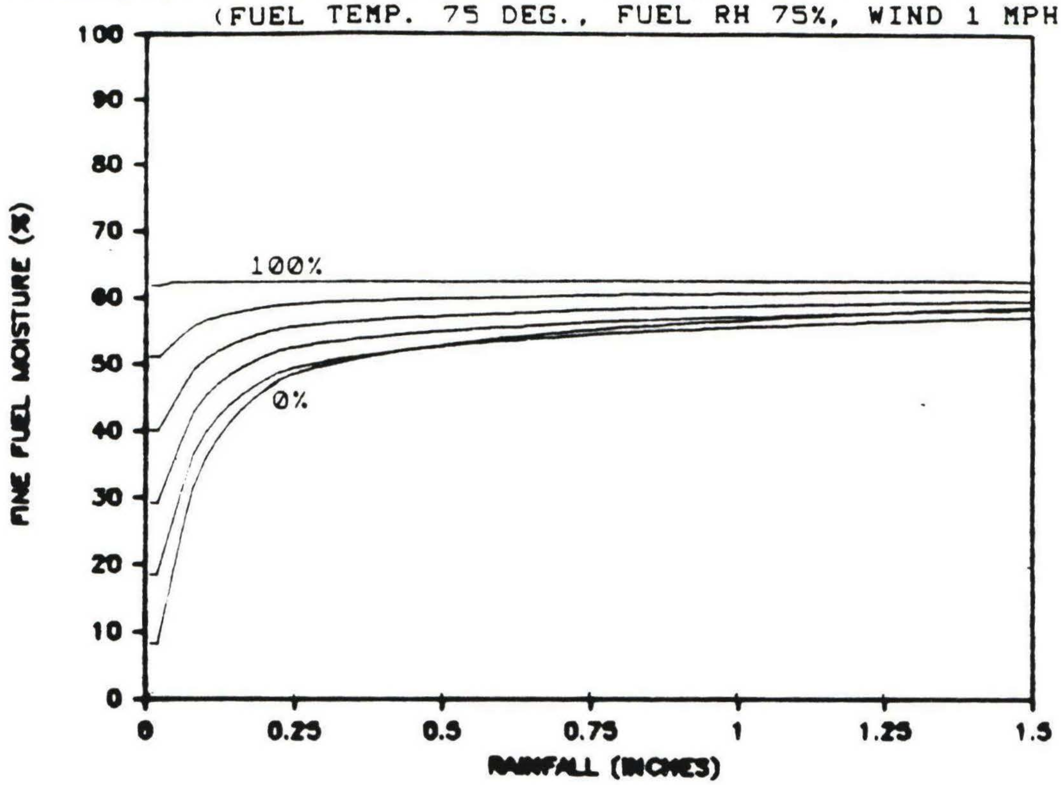


FIGURE B: FFM BY RAINFALL AND INITIAL FUEL MOISTURE
FUEL TEMP. 60 DEG., FUEL RH 75%, WIND 1 MPH)

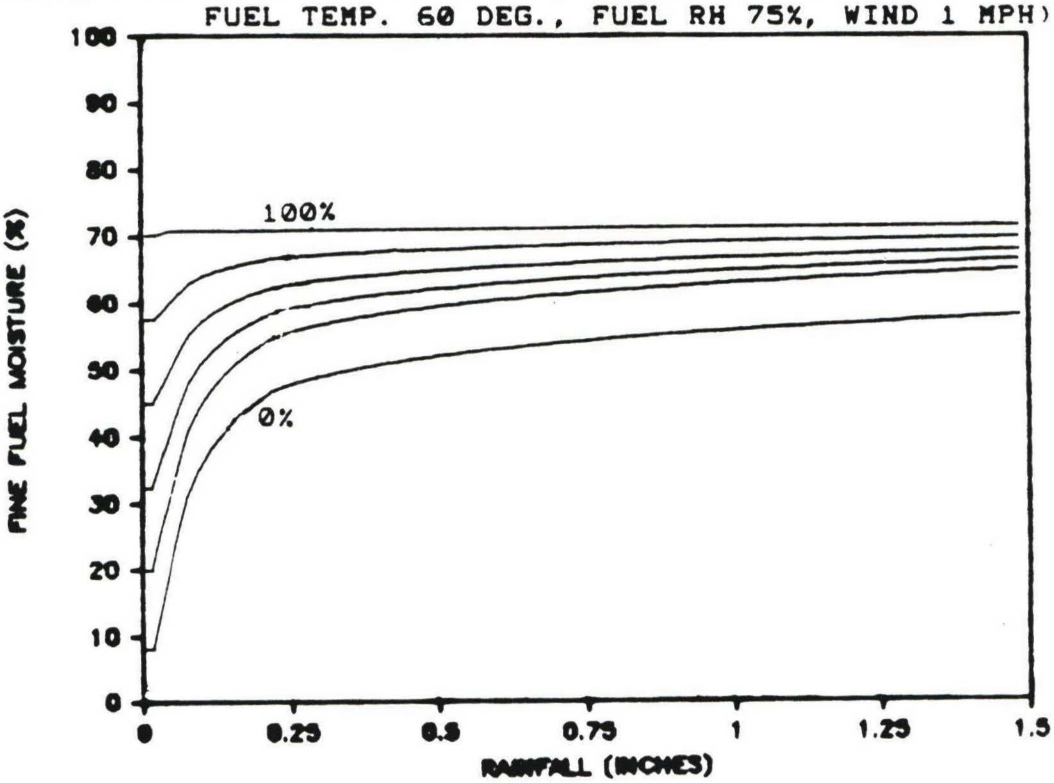


FIGURE A: FFM BY RAINFALL AND INITIAL FUEL MOISTURE
(FUEL TEMP. 100 DEG., FUEL RH 50%, WIND 15 MPH)